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ROLLIN T. CHAMBERLIN

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IN EXPLANATION OF OUR NEW FORMAT

* * *

THIS ISSUE introduces a double-column page, designed for easier reading as well as for economy, in line with wartime necessities. The actual saving is very substantial, and the editor feels that scholarship will be better served by using all available money for the *publication* of research than for such typographical luxuries as wide margins and "white space." Moreover, the shorter reading line is recommended by leading academic reading specialists.

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THE EDITOR

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THE SYSTEM ALBITE-ANORTHITE-SPHENE

A. T. PRINCE

National Research Council, Ottawa, Ontario

ABSTRACT

The phase-equilibrium relationships at atmospheric pressure and high temperatures in the systems albite-sphene, anorthite-sphene and albite-anorthite-sphene were studied. The quenching method was used throughout, and the data for the limiting runs in each system are presented. Equilibrium diagrams have been constructed, and the courses of crystallization of typical mixtures under conditions of equilibrium and perfect fractionation are described. The petrological significance of the investigation is discussed with the aid of a tentative quaternary diagram of the system albite-anorthite-diopside-sphene, in which simplified rock compositions occur.

INTRODUCTION

For practical reasons the selection of systems for thermal investigation under conditions of phase equilibrium is ordinarily governed by the stability of the minerals concerned at atmospheric pressure and high temperature. Thus there has been no general investigation of systems in which such important groups of minerals as the amphiboles and micas appear as phases. Abundance of a mineral in nature and its assumed significance in elucidating the complex story of magmatic differentiation also favor its selection as one of the components of a system to be studied. Accordingly, the accessory minerals as a group have not been investigated to any great extent. It must be remembered, however, that they are often diagnostic of a given intrusive body, serving as key minerals in helping to identify the apophyses of the mass and in a sense being comparable to index fossils. Both fossils and accessory minerals usually represent a small proportion of the rock concerned, yet this is no criterion of their importance. Furthermore various kinds of accessory minerals are characteristic of certain genetic groups of rocks, and investigations of the conditions of their crystallization may well supplement interpretations based on studies of the main constituents of the rock mass.

All three minerals in the present study are well known. Albite and anorthite, comprising the plagioclase series, were selected as typical common and abundant rock-forming minerals whose thermal properties have been determined. Sphene was selected as representing the accessory type, knowing in advance that it acted as a stable component and melted congruently under laboratory conditions.

THE METHOD OF INVESTIGATION

Mixtures were prepared from oxides and carbonates of high purity. Silica was obtained from vein quartz which, after thorough leaching with HCl, contained only 0.03 per cent residue on ignition following treatment with HF and H_2SO_4. A very pure titania, prepared by the Dupont Chemical Company, was used. Alumina was obtained by dehydrating Baker's C.P. $Al_2O_3 \cdot xH_2O$. The source of lime in the mixtures was Baker's C.P. precipitated $CaCO_3$, carefully heated to drive off only the adsorbed water. Soda was added as the anhydrous carbonate, which was obtained by dehydrating Baker's C.P. $Na_2CO_3 \cdot H_2O$.

By mixing weighed amounts of the carbonates and oxides in an agate mortar and fusing several times in a platinum crucible, mixtures of known composition in the form of a homogeneous glass were prepared. Three or more fusions were usually required, and, after each, the charge was removed from the crucible and crushed to a powder in a diamond mortar. Care was taken to remove the particles of steel from the charge with a magnet, before each fusion. The uniformity of the index of refraction of the glass was checked by the immersion method. In color the glass varied from deep amber at the composition of sphene to colorless at the plagioclase join.

The usual equipment and procedure required for the quenching method of thermal investigation, as developed by the Geophysical Laboratory, was used. In general, devitrification of the mixtures prior to making a run in the quench furnace was unnecessary. Calibration of the thermocouples against pure substances was frequently carried out and the necessary corrections made. The calibration materials were: gold, 1,062.6° C.; lithium metasilicate, Li_2SiO_3, 1,201° C.; and diopside, $CaMg(SiO_3)_2$, 1,391.5° C.

PREVIOUS INVESTIGATIONS IN THE SYSTEM

THE SYSTEM ALBITE-ANORTHITE

This binary system[1] is one of the three which bound the ternary system under discussion. It shows a complete series of solid solutions from pure albite to pure anorthite, the equilibrium diagram being so familiar that it need not be reproduced here.

THE SYSTEM ANORTHITE-TITANITE

This system was shown by K. Iwase and Y. Saito[2] to be a simple binary eutectic type, in which the eutectic lies at 62 per cent titanite and 38 per cent anorthite and at a temperature of 1,297° C. In the course of the present study a few mixtures were prepared on the anorthite-sphene join, and liquidus determinations were made. The diagram resulting from this work is shown in Figure 2, and the data from which it was constructed are given in Table 2. The data are in close agreement with those of the earlier investigators, and all due credit for priority is given them, although some minor modifications are suggested by the present work.

THERMAL DATA AND EQUILIBRIUM DIAGRAMS

THE SYSTEM ALBITE-SPHENE

For each of the binary systems and for the ternary system a table is given showing the composition of the mixture, the

[1] N. L. Bowen, "The Melting Phenomena of the Plagioclase Feldspars," *Amer. Jour. Sci.*, Vol. XXXVIII (4th ser., 1913), pp. 577–99.

[2] "The Equilibrium Diagram of the System Anorthite ($CaO \cdot Al_2O_3 \cdot 2SiO_2$)–Titanite ($CaO \cdot TiO_2 \cdot SiO_2$)," *Science Repts. Tokohu Imperial University*, Vol. XXIII (2d ser., 1934), p. 539.

duration of the run, and the condition of the charge at equilibrium.

The data given in Table 1 have been used to construct the equilibrium diagram for the system (Fig. 1). Points actually determined are shown in solid black dots, representing in most cases

TABLE 1

THERMAL DATA FOR THE SYSTEM ALBITE-SPHENE

Composition Weight Per Cent		Time	Temperature (Centigrade)	Condition at Equilibrium
Albite	Sphene			
95.0	5.0	24 hr.	1,127°	A trace of plagioclase in glass; just at the liquidus temperature
92.5	7.5	24	1,127	A trace of sphene and plagioclase in glass; just at liquidus and at the break in the curve
90.0	10.0	60 min.	1,150	Small prismatic sphene crystals in glass
90.0	10.0	30	1,154	All glass
80.0	20.0	60	1,226	Prismatic sphene crystals in glass
80.0	20.0	60	1,232	All glass
70.0	30.0	50	1,270	Sphene crystals in glass
70.0	30.0	50	1,274	All glass
60.0	40.0	60	1,286	Rounded sphene crystals in glass
60.0	40.0	60	1,292	All glass
50.0	50.0	30	1,298	Abundant small sphene crystals in glass
50.0	50.0	30	1,302	All glass
40.0	60.0	35	1,307	Sphene crystals in glass
40.0	60.0	35	1,313	All glass
30.0	70.0	30	1,322	Euhedral sphene crystals in glass
30.0	70.0	30	1,326	All glass
20.0	80.0	30	1,337	Sphene crystals in glass
20.0	80.0	30	1,341	All glass
10.0	90.0	30	1,360	Sphene crystals in glass
10.0	90.0	30	1,364	All glass
0	100.0	10	1,384	Mostly sphene; a trace of glass
0	100.0	20	1,388	All glass

mixtures at successive 10 per cent intervals of composition.

The liquidus curve for the system is shown, passing from 1,386° C., the melting-point of pure sphene, to albite, where the melting-point is 1,118° C., with a break at 92.5 per cent albite. This curve is the temperature-composition boundary, above which all is liquid and below which crystals may exist in equilibrium with liquid. The curve represents a univariant condition throughout most of its length, that is, between sphene and the break at 92.5 per cent albite. From sphene as far as this point it is a true binary system in which both phases can be expressed in terms of the two components.

From the break in the curve to pure albite, the system is no longer binary, for the break is a little above the melting-point of pure albite. The primary phase in this region is not albite but a plagioclase close to it in composition. The formation of a plagioclase that contains

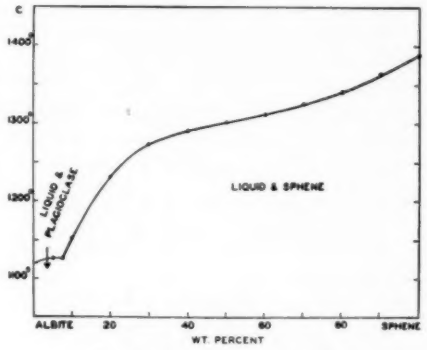

FIG. 1.—The system albite-sphene

even a small amount of lime indicates that the liquid in equilibrium with it has been robbed of some of its lime and that neither composition can be represented in terms of two components.

The equilibrium crystallization of mixtures on the sphene side of the break begins with the formation of sphene crystals. As the temperature falls, the proportion of sphene crystals increases, and the liquid becomes progressively more albitic until it reaches the composition shown by the break in the curve. At this temperature and composition the liquid phase begins to move out of the binary system, as albite-rich plagioclase crystallizes together with sphene. Actually the liquid moves along the extension of the ternary boundary curve beyond

the triangle, but detailed discussion must be postponed until the ternary data have been presented.

A mixture on the albite side of the break begins crystallization with the separation of a plagioclase close to albite in composition, and the liquid immediately moves out of the binary system. The behavior of such mixtures will be made clear when the ternary system is discussed.

THE SYSTEM SPHENE-ANORTHITE

As stated previously,[3] this system was studied by other investigators prior to the present work, but minor changes were considered necessary on the basis of the data given in Table 2. From the data

TABLE 2

THERMAL DATA FOR THE SYSTEM SPHENE-ANORTHITE

Composition Weight Per Cent		Time	Temperature (Centigrade)	Condition at Equilibrium
Anorthite	Sphene			
30	70	30 min.	1,314°	Sparse sphene crystals in glass
30	70	30	1,318	All glass
36	64	30	1,303	Rare traces of sphene in glass, hence run is at liquidus
38	62	30	1,304	Many irregular anorthite crystals in glass
38	62	30	1,306	All glass
50	50	30	1,368	A few ragged anorthite crystals in glass
50	50	30	1,372	All glass
70	30	25	1,450	Many euhedral anorthite crystals in glass
70	30	25	1,454	All glass

in this table the equilibrium diagram for the system sphene-anorthite (Fig. 2) was constructed. The eutectic temperature is placed at 1,301° C., which is 4° C. higher than in the earlier study, and the eutectic composition is located at 63 per cent sphene and 37 per cent anorthite, which is 1 per cent closer to sphene. The system is a simple binary eutectic type and shows no unusual features.

[3] See p. 2.

THE SYSTEM ALBITE-ANORTHITE-SPHENE

Thermal data and equilibrium diagram.—In this system a large number of mixtures were made up mostly from the constituent oxides and carbonates, but in some cases they were made up by mixing glasses that had already been prepared. For almost all mixtures, liquidus determinations were made, but, for some, secondary-phase determinations were also made, that is, the temperature was found where the second solid phase began to crystallize. Most of the secondary-phase

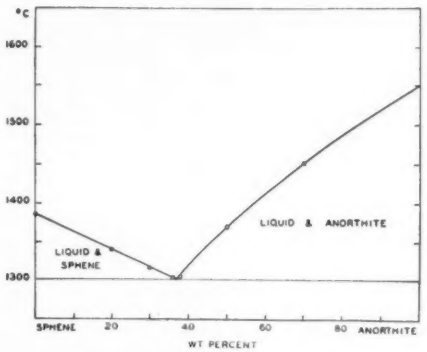

FIG. 2.—The system albite-anorthite

determinations were made in the part of the diagram where plagioclase is the primary phase (plagioclase field), but a few were made on mixtures lying in the sphene field.

The data given in Table 3 have been used in the compilation of Figure 3, which shows the boundary curve and the isotherms of the liquidus surface. The circles show the compositions of mixtures, both binary and ternary, that have been prepared in the study, most of which were used for liquidus determinations. The system is of a simple ternary nature in all but the 25 per cent of its area, adjacent to the albite-sphene join. Toward the last stages of crystallization, the liquid phase of all mixtures in this

area migrates beyond the limit of the diagram along the extension of the boundary curve. Where this occurs, the liquid phase can no longer be expressed in positive quantities of the three components at the corners of the triangle, but the system remains ternary until such time as a solid phase other than sphene or plagioclase separates from it.

Figure 3 is a projection of a three-dimensional model in which the temperature axis is perpendicular to the plane of the paper. Such a model would show a single trough descending with increasing gradient from the anorthite-sphene eutectic at *E*, to the break in the curve of the albite-sphene diagram at *F*. In the bottom of the trough is the boundary curve represented by the curved line *EF*, which separates the field of sphene from the field of plagioclase. As used here and throughout this paper, the word "field"

TABLE 3

LIQUIDUS DETERMINATIONS ON TERNARY MIXTURES

	Composition Weight Per Cent			Time	Temperature (Centigrade)	Condition at Equilibrium
	Albite	Anorthite	Sphene			
	92.00	4.00	4.00	10 hr.	1,163°	A trace of small euhedral plagioclase crystals; right at liquidus temperature
	86.00	6.00	8.00	5	1,181	Sparse plagioclase crystals in glass
	86.00	6.00	8.00	5	1,185	All glass
	83.00	6.00	11.00	4½	1,169	Plagioclase crystals in glass
	83.00	6.00	11.00	4½	1,173	All glass
	82.00	12.00	6.00	2½	1,243	A trace of plagioclase in glass
	78.50	9.50	12.00	3	1,199	A trace of plagioclase in glass
	75.00	15.00	10.00	45 min.	1,257	A few plagioclase crystals in glass
	75.00	15.00	10.00	45	1,261	All glass
	71.00	13.00	16.00	2 hr.	1,215	A trace of plagioclase crystals in glass
	60.00	30.00	10.00	30 min.	1,349	A trace of plagioclase crystals in glass
	60.00	18.00	22.00	45	1,235	Both plagioclase and sphene crystals in glass
	60.00	18.00	22.00	45	1,239	All glass
	51.25	36.25	12.50	30	1,362	Plagioclase crystals in glass
	51.25	36.25	12.50	30	1,366	All glass
Primary Phase Plagioclase	51.50	28.00	20.50	30	1,300	Plagioclase crystals in glass
	51.50	28.00	20.50	30	1,304	All glass
	43.00	26.00	31.00	30	1,267	Very rare plagioclase crystals in glass
	42.50	42.50	15.00	20	1,380	Plagioclase crystals in glass
	42.50	42.50	15.00	20	1,384	All glass
	33.33	33.33	33.33	35	1,293	Plagioclase crystals in glass
	33.33	33.33	33.33	35	1,297	All glass
	31.25	51.25	17.50	30	1,407	Plagioclase crystals in glass
	31.25	51.25	17.50	30	1,411	All glass
	30.75	30.75	38.50	30	1,278	A few large plagioclase crystals in glass
	30.75	30.75	38.50	30	1,282	All glass
	26.66	46.66	26.66	30	1,373	Plagioclase crystals in glass
	26.66	46.66	26.66	20	1,377	All glass
	16.66	43.33	40.00	30	1,340	Plagioclase crystals in glass
	16.66	43.33	40.00	30	1,344	All glass
	15.00	35.00	50.00	25	1,282	Plagioclase crystals in glass
	15.00	35.00	50.00	25	1,286	All glass
	8.33	56.67	35.00	20	1,404	Plagioclase crystals in glass
	8.33	56.67	35.00	20	1,408	All glass
	7.50	42.50	50.00	30	1,331	Plagioclase crystals in glass
	7.50	42.50	50.00	30	1,335	All glass

TABLE 3—*Continued*

	Composition Weight Per Cent			Time	Temperature (Centigrade)	Condition at Equilibrium
	Albite	Anorthite	Sphene			
Primary Phase Sphene. . . .	86.90	3.10	10.00	4 hr.	1,155°	Trace of sphene in glass
	78.80	7.20	14.00	2	1,190	Tiny sphene laths in glass
	78.80	7.20	14.00	2	1,194	All glass
	78.00	6.00	16.00	2	1,215	Trace of sphene in glass
	71.00	8.00	21.00	50 min.	1,236	Small sphere crystals in glass
	71.00	8.00	21.00	50	1,240	All glass
	62.00	16.00	22.00	45	1,234	Some sphene crystals in glass
	62.00	16.00	22.00	45	1,238	All glass
	56.50	11.50	32.00	30	1,265	Small euhedra of sphene in glass
	56.50	11.56	32.00	30	1,269	All glass
	46.50	13.00	40.50	30	1,281	Euhedra of sphene in glass
	46.50	13.00	40.50	30	1,285	All glass
	43.00	23.00	34.00	30	1,260	Trace of sphene crystals in glass
	37.50	12.50	50.00	30	1,204	Some sphene crystals in glass
	37.50	12.50	50.00	30	1,298	All glass
	30.00	10.00	60.00	30	1,309	Trace of sphene crystals in glass
	28.00	28.00	44.00	30	1,276	Good sphene crystals in glass
	28.00	28.00	44.00	30	1,280	All glass
	25.71	10.00	64.29	30	1,314	Trace of sphene crystals in glass
	25.00	25.00	50.00	30	1,283	Sphene crystals in glass
	25.00	25.00	50.00	30	1,287	All glass
	20.00	20.00	60.00	30	1,304	Sphene crystals in glass
	20.00	20.00	60.00	30	1,308	All glass
	20.00	5.00	75.00	25	1,331	Sphene crystals in glass
	20.00	5.00	75.00	30	1,335	All glass
	14.00	34.00	52.00	30	1,279	Both sphene and plagioclase crystals in glass
	14.00	34.00	52.00	30	1,283	All glass
	10.00	10.00	80.00	30	1,344	Trace of sphene crystals in glass
	10.00	20.00	70.00	30	1,321	Sphene crystals in glass
	10.00	20.00	70.00	30	1,325	All glass
	7.00	32.00	61.00	30	1,301	Rare sphene crystals in glass

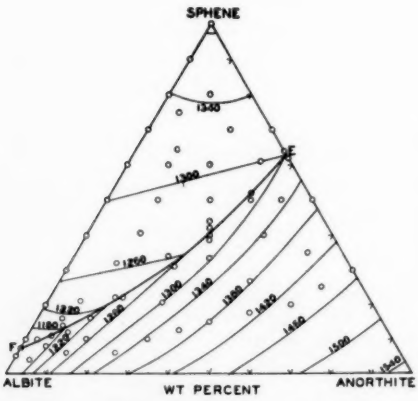

FIG. 3.—The system albite-anorthite-sphene

when applied to a diagram means the portion of the diagram where the phase mentioned is primary.

On each side of the boundary curve the liquidus surfaces rise to maximum points, one at anorthite representing a temperature of 1,550° C., the other at sphene, where the fusion point is 1,386° C. The surface representing the sphene field is relatively flat throughout most of its extent but steepens rapidly on approaching the boundary curve, especially near *F*. The liquidus surface is much steeper in the plagioclase field than in the sphene field, as can be seen from the close spacing of the isotherms.

Degrees of freedom in the system.—There are no invariant points in the ternary system, because at no composition can three solid phases exist in equilibrium with liquid, as in the case of a ternary eutectic. The complete solid solution of the plagioclases is responsible for this feature, since two mutually soluble solid phases form but one phase, a mix-crystal.

The boundary curve is the locus of points of univariant equilibrium in a condensed system, representing a condition where one liquid and two solid phases can coexist in equilibrium. A point on the boundary curve represents the composition of a liquid which is in equilibrium with sphene and a plagioclase solid solution as defined by a three-phase boundary. The manner in which three-phase boundaries define the composition of the plagioclase in equilibrium at any point will be described later. Thus at a point on the boundary curve only one variable need be fixed in order to define the system. If, for example, a temperature is given at which three phases coexist in this system, the composition is automatically fixed at a definite point on the boundary curve. Conversely, if a composition is stated where three phases are present in equilibrium, the temperature is thereby defined in a condensed system.

Secondary-phase determinations.—In order to understand the system completely, it was necessary to make determinations of the temperatures where the secondary phases began to crystallize from certain mixtures. Most of the mixtures selected had compositions lying within the plagioclase field, since these can be used to find the useful three-phase boundaries in the solid solution field. This type of three-phase boundary is especially important, because, when it is known, a three-phase triangle for that temperature can be constructed. The significance of the three-phase triangle will be made clear when the courses of crystallization in the ternary system are discussed. In Table 4 the data for the secondary-phase determinations are given.

The data given in Table 4 have been used to construct the three-phase boundaries in the plagioclase field shown in Figure 4. These boundaries may be determined in a number of ways, but in this study the temperature method was used. In order to use this method, the boundary curve must have been determined previously, for each secondary-phase temperature point, necessarily a point on the boundary curve, fixes one end of the three-phase boundary for that temperature.

A section through the diagram following the boundary curve is therefore useful, and such a section with temperature plotted against weight-per cent albite from E to F is given in Figure 5. The diagram shows a moderately steep but diminishing gradient from E to an inflection point near 20 per cent albite, after which it begins to steepen as F is approached. Curves of this general shape are characteristic of the fusion surface of the sphene field. The points shown by open circles in Figure 5 are arbitrary intercepts along the boundary curve where temperature and composition were read for plotting the curve.

To each secondary-phase temperature there corresponds a liquid composition which may be stated in terms of weight-per cent albite as shown. These points, once found, may be transferred to the ternary diagram, where they appear as points on the boundary curve. By joining each of them to the point representing the initial composition of the corre-

TABLE 4

SECONDARY-PHASE DETERMINATIONS ON TERNARY MIXTURES

	Composition Weight Per Cent			Time	Temperature (Centigrade)	Condition at Equilibrium
	Albite	Anorthite	Sphene			
Secondary Phase Sphene	92.00	4.00	4.00	21½ hr.	1,106°	A trace of very small sphene crystals with plagioclase in glass
	75.00	15.00	10.00	1	1,181	A trace of sphene with abundant plagioclase in glass
	60.00	30.00	10.00	45 min.	1,204	Plagioclase with some sphene crystals in glass
	60.00	30.00	10.00	45	1,208	Plagioclase crystals in glass
	51.25	36.25	12.50	45	1,235	A trace of sphene with abundant plagioclase in glass
	42.50	42.50	15.00	30	1,246	Abundant plagioclase with a few small sphene crystals in glass
	42.50	42.50	15.00	30	1,250	Plagioclase in glass
	31.25	51.25	17.50	30	1,266	Abundant plagioclase with a trace of sphene crystals in glass
	26.66	46.66	26.66	45	1,273	Abundant plagioclase with a trace of sphene crystals in glass
	20.00	60.00	20.00	30	1,277	A mere trace of sphene with abundant plagioclase crystals in glass
	8.33	56.66	35.00	30	1,285	Abundant plagioclase with some sphene in glass
	8.33	56.66	35.00	30	1,289	Abundant plagioclase in glass
Secondary Phase Plagioclase	62.00	16.00	22.00	45	1,224	Rare plagioclase crystals with sphene in glass
	43.00	23.00	34.00	35	1,250	Rare plagioclase crystals with some sphene in glass
	43.00	23.00	34.00	30	1,254	Abundant sphene in glass

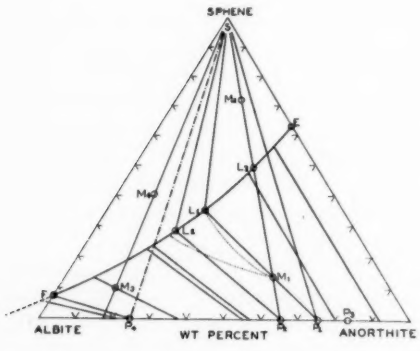

FIG. 4.—The system albite-anorthite-sphene, showing the boundary curve and three-phase boundaries in the plagioclase field, with two complete three-phase triangles, SL_1P_1 and SL_2P_2.

sponding mixture one obtains the appropriate three-phase boundary.

Two complete three-phase triangles have been constructed in Figure 4. These are but two of an infinite number of such triangles that could be constructed over the range of temperatures from E to F along the boundary curve. Each of the triangles constructed indicates the equilibrium condition prevailing at the temperature given by the corner on the boundary curve. The three phases concerned in a particular case are represented in composition by the corners of the triangle. Thus in the triangle SP_1L_1 (Fig. 4) the phases concerned are a plagioclase of composition $Ab_{25}An_{75}$, sphene, and liquid as shown by the corner on the boundary curve at L_1.

Equilibrium crystallization of normal ternary mixtures.—Mixtures lying to the right of the line P_4S are normal ternary mixtures because the compositions of all phases throughout the process of crystallization can be expressed in positive quantities of the components. This area is 75 per cent of the whole triangle. In the plagioclase field a mixture such as M_1 begins to crystallize with the separation of a plagioclase of composition near anorthite, as

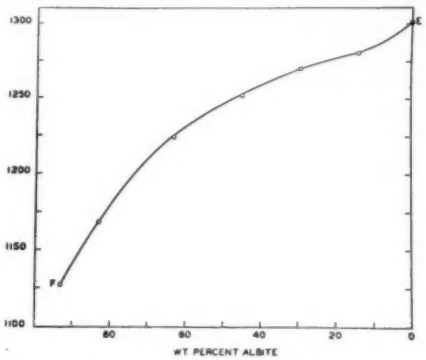

FIG. 5.—Boundary curve section

shown by the tangent to the curve M_1L_1 at M_1 projected to cut the Ab–An join. As cooling and crystallization proceed, the liquid composition changes along a curve such as M_1L_1, while plagioclase continues to increase in quantity and change in composition toward albite. Under equilibrium conditions all the plagioclase present at any point along the liquid migration curve M_1L_1 has the composition of the plagioclase crystallizing from that particular liquid. The reason for this is that the more anorthitic plagioclase formed earlier in the process is progressively made over through contact with liquid. The plagioclase in equilibrium with liquid L_1 has a composition $Ab_{25}An_{75}$. At this point sphene begins to crystallize, and the liquid is forced to move along the boundary curve, with both solid phases separating. Plagioclase composition continues to change in the direction of albite as liquid follows the boundary curve, and at any temperature the plagioclase composition can be found by interpolating a three-phase boundary from that temperature on the boundary curve. The proportion of phases present can be found by completing the three-phase triangle and by measuring the length of perpendiculars from the point of initial composition to the three sides. When L_2 has been reached, all the liquid has disappeared and the plagioclase has changed to P_2, $Ab_{35}An_{65}$. The mixture M_1, now composed of SM_1 parts of P_2 and P_2M_1 parts of sphene, cools without further change in the composition of its constituents.

In the sphene field the equilibrium crystallization of a mixture is much less complicated. A mixture such as M_2 begins to crystallize with the separation of sphene, and the liquid changes composition along a straight line directly away from S. This continues until the liquid reaches L_3, where plagioclase of composition P_3 begins to form. Liquid composition moves along the boundary curve through L_1 to L_2, all the plagioclase changing progressively from P_3 to P_2 in composition as it increases in amount. When L_2 is reached, all the liquid has disappeared, and the mixture consists of solid sphene and plagioclase P_2. The crystallization of any mixture along the line SP_2 gives the same phases, but the relative proportion of the two crystalline phases varies with the position of the mixture on the line.

Equilibrium crystallization of special mixtures.—Mixtures to the left of the line P_4S in an area comprising about 25 per cent of the diagram are somewhat specialized because the last of the liquid

to crystallize has a composition lying on the extension of the boundary curve outside the triangle. Mixtures lying close to the line P_4S within this area can be considered normal throughout most of their course of crystallization, but in the final equilibrium crystallization is merely sphene and plagioclase. An equation can be written to show the reaction between sphene and albite whereby a plagioclase and a complex hypothetical sodium titanosilicate are formed. This may be

$$\underset{\text{Sphene}}{CaTiSiO_5} + 2\underset{\text{Albite}}{NaAlSi_3O_8} \rightleftarrows \underbrace{\underset{\text{Anorthite}}{CaAl_2Si_2O_8}}_{\text{Plagioclase}} + \underbrace{Na_2TiSi_5O_{13}}_{\text{Hypothetical}}.$$

As solid phases and in the early part of the residual liquid — In the late residual liquid

stages, where the liquid passes beyond F, it has a somewhat unusual composition and cannot be expressed in positive quantities of the three components. Liquids lying beyond F are deficient in lime and alumina, because an albitic plagioclase crystallizes in preference to pure albite. This results in an excess of silica, titania, and soda in these liquids, while more than the normal amount of lime and alumina are locked up in the solid phases. Nevertheless, the composition of the liquid phase can be expressed as albite plus sphene minus anorthite, and the system remains ternary until an additional solid phase crystallizes.

A mixture such as M_3, with a composition lying in the plagioclase field, crystallizes in similar manner to M_1, following a curved course to the boundary curve where sphene begins to separate. Sphene and plagioclase crystallize together, while the latter is made more albitic through a continuous reaction with the liquid phase. The mixture behaves as a simple ternary one until the liquid phase reaches F, at which time the plagioclase in equilibrium with it is P_4. Beyond F, sphene and plagioclase continue to form, and the final composition of the solid-solution crystals is about $Ab_{82.5}An_{17.5}$. Unless the field of a new phase is encountered between F and the point where all the liquid disappears, the final result of the considered as an equilibrium reaction between reciprocal salt pairs as in the above formula.

The hypothetical sodium titanosilicate may be considered to decompose to the following known compounds, which, for convenience, we shall refer to as additional phases:

$$Na_2TiSi_5O_{13} \rightleftarrows Na_2Si_2O_5 + TiO_2 + 3SiO_2.$$

It is probably the field of one of these compounds that the liquid encounters on the extension of the boundary curve. Mixtures in an area of unknown extent close to the albite-sphene join, within the triangle, and on the join from near the break in the curve to sphene itself must give crystals of sphene, a plagioclase, and some of these additional phases before solidification is complete. When the additional phase appears, the system ceases to be ternary. Mixtures near the albite end of the albite-sphene join and in the adjacent area of the ternary diagram will crystallize to an albitic plagioclase of definite composition and the group of additional phases, while sphene itself will not appear as one of the phases.

Within the scope of the present study it was not possible to investigate the equilibrium conditions along the extension of the boundary curve. It was possible, however, to follow the curve beyond the triangle with the solid phase

still plagioclase and not albite. From this fact and from a comparison with more simple but fundamentally analogous systems that have been investigated, the above generalized behavior is indicated.

Perfect fractional crystallization.—Fractional crystallization occurs if solid phases are prevented from reaction with liquid in systems where the solid phase is a mix-crystal or where it possesses an incongruent melting-point. The conditions which cause it are too rapid cooling, the gravitative settling of the solid phase so that it fails to react with liquid, failure to stir the melt, and the zoning of the solid phase in such a way that successive layers of different composition serve as an armor against reaction between the inner zones and the liquid. Only the outermost zone, one of infinitesimal thickness, is in actual equilibrium with liquid at a given instant under conditions of perfect fractionation. Zoning and gravitative separation are the dominant factors in the operation of this principle in nature. Perfect fractionation and perfect equilibrium are the extremes of possible behavior in the cooling melt, and between them lie an infinite number of intermediate methods of crystallization, all included in the term "imperfect fractionation." In fact, the cooling of most mixtures would show intermediate behavior, and only an exact adjustment of conditions could produce either of the extreme forms.

Fractional crystallization of mixtures in the plagioclase field may be discussed with the aid of Figure 4. A mixture such as M_1 on crystallizing under conditions of perfect fractionation shows a course of liquid migration that differs considerably from the curve M_1L_1, the equilibrium course. At any point on the curved course of perfect fractionation, the solid phase in equilibrium at that instant is shown by the intercept on the plagioclase join of the tangent at that particular point. The direction of such a course is therefore a curve, starting at M_1, where the temperature is 1,435° C., and moving across the plagioclase field more nearly parallel to the plagioclase join than the curve M_1L_1. It finally reaches the boundary curve at a point close to L_2, and a particular three-phase boundary there is tangent to it. The liquid now follows the boundary curve, as both plagioclase and sphene crystallize together. Since plagioclase has been prevented from reacting with liquid at every stage in the crystallization, the liquid phase persists to a much lower temperature and in greater quantity than when equilibrium conditions prevail. The effect of fractionation is thus to increase the quantity of liquid still present at lower temperatures and to force it toward a more acid composition. On continued cooling the liquid passes beyond F, and at some undetermined temperature other phases in addition to plagioclase and sphene will appear. The nature of these new phases is not definitely known, but suggestions have been made above in discussing equilibrium crystallization of certain mixtures.

With perfect fractionation any mixture in the plagioclase field will yield at least some liquid on the extension of the boundary curve, but if the mixture lies close to the anorthite-sphene join, the amount of this liquid will be almost infinitely small. The amount of such liquid increases as mixtures approach the albite-sphene join.

The fractional crystallization of a mixture such as M_2 in the sphene field begins at a temperature of 1,325° C. with the separation of sphene crystals. The course of crystallization through the sphene field is always a straight line, regardless

of whether the crystals once formed are left in contact with liquid or are removed.

However, when the boundary curve is reached by the liquid phase originating from M_2, plagioclase of composition P_3 begins to form, and from this point on fractionation will occur if plagioclase crystals fail to be made over by reaction with liquid. The result as before is that liquid composition is offset toward albite and down the temperature gradient.

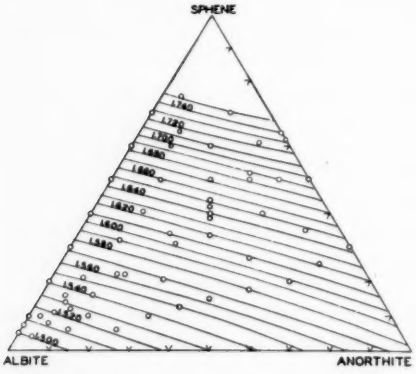

FIG. 6.—The composition-refractive index diagram for glasses.

Starting with M_2, it is possible for a small quantity of liquid to pass to compositions beyond F. The closer a mixture in the sphene field lies to the albite side of the diagram, the greater is the quantity of liquid of that character that can form.

The composition refractive index diagram.—In Figure 6 the indices of refraction of homogeneous glass mixtures are plotted against weight per cent of the components. Each curve shown in the diagram is the locus of points having the same index of refraction. In making up mixtures, the diagram is very helpful because it offers a rapid method of checking the composition of a given mixture. The glass is finely pulverized and a small sample of it examined under the microscope for uniformity as shown by the immersion method. When by repeated grinding and fusion the mixture has been rendered uniform, as shown by its refractive index, and the value for the index has been found, it is ready for thermal investigation. The curves of equal refractive index are normally quite smooth and usually approach straight lines. A departure of the index of any glass from the value indicated by the smooth curves suggests that the mixture is off composition.

PETROLOGICAL SIGNIFICANCE

SIMPLIFIED ROCK COMPOSITIONS REPRESENTED IN THE TETRAHEDRON ALBITE-ANORTHITE-DIOPSIDE-SPHENE

In thermal behavior sphene is remarkably similar to diopside, the former having a congruent melting-point at 1,386° C., the latter at 1,391.5° C. In the system albite-anorthite-diopside[4] the phase diagram is similar to the present system, having two fields separated by a single boundary curve. The system diopside-anorthite is a simple eutectic type, resembling the system sphene-anorthite. The system diopside-albite was considered a simple eutectic type in the above investigation.[5] More recent work,[6] however, has shown it to be similar to the system albite-sphene, where there is a break in the curve and not a simple eutectic.

In considering simple systems representative of rock compositions, it is inadequate to deal with sphene and plagioclase alone, and in the present discussion diopside has been included as a nec-

[4] Bowen, "The Crystallization of Haplobasaltic, Haplodioritic and Related Magmas," *Amer. Jour. Sci.*, Vol. XL (4th ser., 1915), p. 167.

[5] *Ibid.*, p. 165.

[6] Personal communication from N. L. Bowen, based on unpublished work by Schairer and Bowen.

essary constituent. It has been shown by Bowen that points near the boundary curve in the system albite-anorthite-diopside have certain analogies with common basic and intermediate igneous rocks.[7] While it is admitted in the above work that the similarity in composition does not justify the assumption that the crystallization process is identical in the artificial and natural systems, it is pointed out that the trends in the two cases must be very much alike. Certain complications arise in the natural magma which cannot be duplicated under laboratory conditions. These involve the complex nature of the natural crystalline phases and the presence of volatiles. This is acknowledged as a difference which cannot be altogether ignored, but it is considered to have very little effect on the trend of crystallization indicated by laboratory investigations. The dominant parameters governing equilibria of this type are temperature and the composition of the liquid and solid phases, while the pressure plays but a secondary role.

In considering the tetrahedral representation of rock compositions having a small TiO_2 content as the mineral sphene, $CaTiSiO_5$, the points concerned must lie within the tetrahedron, but fairly close to the albite-anorthite-diopside face. If we assume the rock to contain 2 per cent TiO_2, and this is not excessive, we have then a potential source of 5 per cent sphene.

In Figure 7 the points D and B, respectively, represent a simplified diorite and a simplified basalt composition. At points one-twentieth of the way along lines joining D and B to the sphene corner, the compositions of the simplified rock types containing 2 per cent TiO_2 are shown as D^1 and B^1. This system has been constructed from a knowledge of three of its constituent ternary systems. While no quaternary mixtures were studied in the present investigation, there can be little doubt as to the trend of crystallization within the tetrahedron, even though the exact proportions or compositions of all the phases concerned cannot be stated. The exact location of the quaternary boundary line as well as the position of

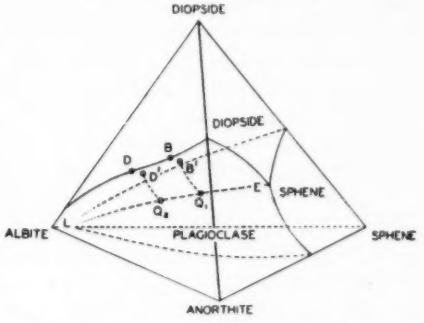

FIG. 7.—The quaternary system, albite-anorthite-diopside-sphene.

the four-phase boundary planes would have to be known in order to work out the composition of the liquid phase and the plagioclase in equilibrium at any time during crystallization. Such a study becomes very complex, but the general behavior of the quaternary system can be readily followed if the ternary type is clearly understood.

CRYSTALLIZATION IN THE QUATERNARY SYSTEM ALBITE-ANORTHITE-DIOPSIDE-SPHENE

The equilibrium crystallization of a mixture such as B^1, which is suggestive of the average basalt, will begin with the formation of either plagioclase or diopside, depending on the exact location of this point with respect to the diopside-plagioclase boundary surface. Cooling of

[7] Bowen, "The Crystallization of . . . . ," *op. cit.*, p. 184.

the mixture causes a migration of the liquid composition toward that boundary surface. When this is reached, the primary phase is joined by the secondary phase, and, as both crystallize, the liquid moves along the boundary surface, following a rather complex course B^1Q_1, which is a curve upon a curved surface within the tetrahedron. When the quaternary boundary EL is reached, sphene begins to crystallize along with plagioclase and diopside. Very little liquid remains by the time the quaternary boundary is reached, but, on any reasonable assumption as to the position of the curve EL, this liquid is comparatively rich in sphene. The significance of this in the crystallization of actual magmas of the basic type is that sphene should not begin to form, if at all, until the later stages, when the liquid remaining had become fairly concentrated in it, as a result of the earlier separation of pyroxene and plagioclase. It is easy to see that this is true also of a liquid of composition D^1 though not in the same degree, since Q_2 lies at a much smaller sphene concentration than Q_1. By no possible mechanism can sphene be made to crystallize first from mixtures of these simplified dioritic or basaltic composition. Its behavior would thus be at variance with the common assumption as to the universal early separation of a minor accessory. This fact is, perhaps, of no practical importance in connection with the crystallization of actual gabbroic magmas, for from such magmas TiO_2 separates partly in the form of ilmenite, $FeTiO_3$, and partly in solid solution in pyroxene. The field of sphene is not ordinarily encountered in their crystallization, and no sphene forms unless the crystallization is fractional and the residual liquid is offset toward acidic compositions.

TITANIFEROUS ACCESSORY MINERALS IN THE ACID ROCKS

It is in rocks of granodioritic type that sphene is most abundant, if one overlooks certain rare alkaline rocks such as sphenetite, where it is a major constituent. It is obvious from relations in the tetrahedron that liquid of granodioritic composition must become saturated in sphene at a much lower concentration than basic liquids. In such rocks the total quantity of sphene is ordinarily of the order of 1 or 2 per cent, and it apparently crystallizes early, when the rock is largely liquid. Such behavior would be in entire accord with the findings of the present study.

The mineral rutile TiO_2, a very common accessory in the granites and to some extent in the diorites, should be mentioned in this connection. In the discussion of the system albite-anorthite-sphene,[8] an equation was written indicating the type of reaction that must take place near the albite corner of the system. It was pointed out that albite tends to rob the liquid phase of lime and alumina and to favor crystallization as an albitic plagioclase. The same type of reaction must occur in the system albite-anorthite-diopside and also in the more complex quaternary system that has been used to illustrate the behavior of simple rock compositions during crystallization. As shown in the equation there is reason to believe that TiO_2 is released in this reaction, so that one would expect to find the mineral rutile in the late residual product of crystallization along with free quartz and a sodium silicate. The latter is not known as a mineral in igneous rocks, and this might be considered as a weakness in the above argument. However, it must be remembered that in the end-product reactions of magmatic

[8] See p. 10.

differentiation the hydrous phase which is responsible for vein formation and mineralization begins to assert itself. Sodium silicates are soluble in hot water, in some cases with decomposition, whereby silica is released, and this is adequate to account for the absence of sodium silicates as rock-forming minerals. The suggested reaction may thus be the principal factor in the formation of alkaline solutions from which quartz may form.

The inclusions commonly found in the quartz of granites and pegmatites are of interest in view of the decomposition reaction given.[9] If we take the products that have been grouped as constituents of the residual liquid, namely, sodium disilicate, rutile, and quartz, an interesting possibility arises. The needle-like inclusions of rutile often found in quartz may have originated from the TiO_2 released in this reaction. It may even be suggested that the accompanying sodium silicate, decomposed by the reaction of water containing chloride ion, may form sodium chloride solution which is imprisoned, upon further growth of quartz, to form brine inclusions.

The rutile grains frequently found in igneous rocks and classed as minor accessories are reputed to be among the first solid phases to crystallize from the molten rock. They are common in the range from diorite to granite composition, and the tendency to develop automorphic outlines is usually considered ample evidence of their priority in crystallization. The present study cannot be called upon to give complete evidence on this point other than to suggest that, in the absence of sufficient lime in the liquid phase of a rock system, rutile will form in preference to sphene. Certainly there is evidence to indicate a generation of rutile at a very late stage due to the reactions discussed earlier in this section, but petrographic evidence suggests that there may be a much earlier generation of rutile.

The attributed early crystallization of the minor accessory minerals is one of their unusual features and should be accepted with reservation until more evidence is given by actual thermal investigation. When one considers the very low concentration of minor accessories such as rutile, apatite, zircon, etc., in a magma, it is somewhat paradoxical that they should be the first minerals to crystallize. Phase-equilibrium studies show that there is a strong tendency for the constituent with the greatest concentration in a given molten mass to crystallize first, and only when the liquid phase has been enriched in a minor constituent should the latter begin to precipitate. Disparity in the melting-points will counteract this tendency to a certain extent, and it is known that minerals such as albite, having a low melting-point, cause the lowest melting mixture to be drawn relatively close to their own composition. Even so, it is very likely that, in a rock magma, a considerable proportion of the low-melting constituents have formed as solid phases because of their high concentration, before any of the higher melting minor constituents have crystallized. The study of textural relationships and crystal form in thin sections has much to commend it, but it must be admitted that, where an accessory is present with other minerals which are greatly in excess, the relationships seen apply only to the accessory and the grains actually touching it. If, for example, the major constituent is albite and it includes euhedral rutile, we know that the contiguous albite formed after the rutile. This is no proof that all the albite crystals formed after the rutile; in fact,

[9] See p. 10.

there is very good evidence for believing otherwise. If one takes a simple eutectic diagram with the eutectic drawn over to 95 per cent by weight of the low-melting component and assumes the presence of 2 per cent of the higher melting constituent, simple geometry shows that three-fifths of the entire mixture has crystallized as the low-melting component before any of the high-melting minor constituent begins to form. For this reason it is wise to be cautious in the interpretation given to the order of crystallization based on the textural relations of the minor accessories.

ACKNOWLEDGMENTS.—The writer is indebted to the Department of Geology and Paleontology, the University of Chicago, for providing financial aid during the two years in which this work was carried out. To Professor N. L. Bowen, whose constant supervision and help was generously given, the writer is especially grateful.

AGE RELATIONSHIPS OF INTRUSIVE ROCKS AND ORE DEPOSITS IN THE RED LAKE AREA, ONTARIO[1]

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ABSTRACT

The intrusive rocks of the Red Lake area are all of post-Timiskaming age. They have been divided into three general ages of intrusion—early pre-Algoman, late pre-Algoman, and Algoman—and into several subdivisions. Separation into three general ages is based on intrusive relations, lithological differences, and relative amounts of deformation and alteration. In the most complex period, the Algoman, the relative age of different formations is based on intrusive relations and on helium-radioactivity age determinations of hornblende separates from selected representative rocks. A genetic relationship between Algoman granodiorite and later basic dikes, which was suggested by field evidence, is corroborated by radioactivity investigations. This establishes the genetic association of the auriferous quartz veins with both granodiorite and basic dikes.

INTRODUCTION

The relative ages of intrusive rock formations in any of our pre-Cambrian mining areas is becoming a question of ever increasing importance. As the possibility of locating mineralized zones is largely dependent upon an understanding of the structural and genetic relationships between intrusive formations and ore bodies, and as more and more of our prospecting ventures are based on such an understanding, geological data on these questions are of economic as well as of scientific interest.

Geological investigations in the Red Lake area[4] in the Patricia portion of the district of Kenora, northwestern Ontario, have definitely proved the sequence of the intrusive formations and given the interval in which the formation of the ore bodies took place. On the basis of intrusive relationships alone, ten distinct ages have been recognized. On the basis of intrusive contacts, lithological characteristics, and relative amounts of deformation and alteration, the ten ages have been grouped into three periods of magmatic activity, designated as "early pre-Algoman," "late pre-Algoman," and "Algoman." The Algoman granite, the pre-vein and post-vein basic dikes, and the ore deposits are all believed to be genetically related and to represent the final and most important stages of the Algoman period. Field evidence alone does not furnish sufficient data to establish either the position in time of the three general ages or the genetic association of granite, dikes, and ore deposits. Therefore, an attempt was made to learn something of these factors from helium-radioactivity age determinations of hornblende concentrates from selected representative rocks. These investigations

[1] Paper presented before Section IV, Royal Society of Canada, May, 1941.

[2] Geological data were obtained by H. C. Horwood during an investigation of the geology and mineral deposits of the Red Lake area for the Ontario Department of Mines.

[3] Helium and radioactivity determinations were made by N. B. Keevil in the McLennan Laboratory at the University of Toronto.

[4] Horwood, Maps 49A, 49B, Red Lake Area, Ontario Department of Mines.

showed a wide range of helium radioactivities and suggested that the "early pre-Algoman" diorite and the "late pre-Algoman" porphyries were followed by a period of magmatic activity responsible for the formation of basic and acid intrusives, basic dikes, and ore deposits. A definite relationship between helium retentivity and degree of alteration was found for this suite of rocks, indicating a possible method of correction for helium-index results.

Although field relationships have shown the sequence of the intrusive formations in the Red Lake area, their position in the geological column cannot be proved definitely beyond post-Timiskaming and preglacial limits. From consideration of occurrences, lithological character, and degree of alteration, however, it is accepted that they are of pre-Cambrian age. A better knowledge of the time intervals between the several igneous formations and of the actual position in the helium time scale is of particular importance in the Red Lake area for the correct interpretation of the structural and genetic relationships of rock formations and ore deposits. Although observations in the field have shown that some of the ore was introduced between the periods of intrusion of two ages of basic dikes, it can be proved neither that these dikes are closely associated in age nor that they are genetically related to the period of intrusion of the granitic masses.

Chemical analyses of the pre-vein and post-vein basic dikes and mineral recasts, which are presented in Table 3, show striking similarities which indicate a genetic relationship. The absence of mineral associations and textures, which are characteristic of Keweenawan dikes, affords negative evidence for correlation with the Keweenawan. On the other hand, the presence of a mineral assemblage comparable with that of the associated granites, granodiorites, and diorites suggests a common origin with these rocks. As the ore deposits were formed in the interval between the two ages of basic dikes, it is also probable that these deposits are genetically related to the granitic rocks. However, to obtain additional evidence it was decided to study the relative ages of the rocks by measuring the helium which accumulated from the radioactive elements during geological time.

Helium age determination did not seem possible at first. Variations in composition between the several rock formations suggested that results might not be comparable. In addition, the high degree of alteration in some of them, produced both by later periods of magmatic activity and by mineralization, indicated that retention of helium would be variable.

In the last two years it has been found that the helium retentivity of different minerals varies over wide limits and that the loss of helium is most pronounced in the more highly altered rocks. Consequently, the best relative-age determinations have been obtained from less altered rocks, which are themselves directly comparable, or from which comparable minerals can be obtained. The first helium age work on separated minerals[5] suggested that the ferromagnesian minerals possess the highest helium retentivities. More recent work has shown that unaltered minerals with close-packed structures, such as magnetite, pyroxene, and hornblende are most suitable for age determination. However, recent evidence indicates that uncorrected

[5] Keevil, "The Distribution of Helium and Radioactivity in Rocks. 1. Mineral Separates from the Quincy Granite," *Amer. Jour. Sci.*, Vol. XXXVI (1938), pp. 406–16.

TABLE 1

TABLE OF FORMATIONS

Geological Division	Rock Formation and Geological Relationship	Helium* Age in Millions of Years	Estimated Per Cent Probable Error
PRE-CAMBRIAN			
Post-Timiskaming	Post-vein basic dikes	1,320	15
	Intrusive contact		
	Period of formation of ore deposits Pre-vein basic dikes	1,380	10
	Intrusive contact		
	Granite, granodiorite, quartz diorite, quartz porphyry granite	1,275	15
	Intrusive contact		
	Hornblende pyroxenite	1,360	7.5
	Intrusive contact		
Algoman	Quartz diorite, diorite, hornblende diorite, hornblende gabbro, feldspar-diorite porphyry, feldspar-gabbro porphyry	1,360	7.5
	Intrusive contact		
	Hybrid granite: granitic rock with assimilated and included greenstone. Granite, granodiorite, and diorite gneiss	1,400†	.....
	Intrusive contact		
	Granodiorite porphyry: quartz and feldspar porphyry	1,400†	.....
	Intrusive contact		
	Feldspar porphyry: fine-grained feldspar granite porphyry	1,490†	.....
Late pre-Algoman	Intrusive contact		
	Quartz porphyry, quartz-feldspar porphyry, granodiorite porphyry, tonalite porphyry	1,490‡	35
	Intrusive contact		
Early pre-Algoman	Howey diorite, feldspar-diorite porphyry	1,760‡	30
	Intrusive contact		
Timiskaming and Keewatin			

* Calculated from helium retentivities as described in this paper.

† Assumed values; no specimens of these formations were studied by radioactive methods.

‡ Values from heavy-liquid separates.

results are unreliable for purposes of correlation.

In the Red Lake area, as in most pre-Cambrian mining areas, the rocks are not only highly altered but show wide variations in the degree of alteration. If the helium method is to be applicable to areas of economic importance, where a high degree of alteration is the rule rather than the exception, methods must be developed to take into account the effects of such factors on the retention

of helium. If the method must be confined to any particular mineral, such as unaltered primary magnetite, then its application will be almost as limited as the lead method as applied to radioactive minerals. In addition, it may never be certain that such minerals are perfect in so far as retention of helium is concerned.

In this paper a method of calculating helium ages from helium-index determinations and from data supplied from microscopic estimates of mineral composition and degree of alteration is applied to intrusive rock formations of the Red Lake area. It is emphasized that this procedure has not been developed as a general method. However, it is of interest in that it has been successfully applied to the Red Lake intrusive rocks.

ROCK FORMATIONS AND INTRUSIVE RELATIONSHIPS

The various post-Timiskaming intrusive rock formations, and the field and laboratory evidence obtained for their separation into formations and into groups of formations representing periods of magmatic activity, are described in the following paragraphs.

EARLY PRE-ALGOMAN

Howey diorite.—The main mass of Howey diorite is an irregular elongate stock that extends east and west across the north sides of Heyson and Byshe townships. It is generally a medium- to coarse-grained, gray-green, massive rock that has suffered considerable deformation and alteration. A relatively fresh specimen was found to contain 53 per cent andesine-labradorite (Ab_{50} An_{50}); 34 per cent hornblende; 5 per cent biotite; and small amounts of chlorite, quartz, epidote, sericite, carbonate, and magnetite. The more common altered types, however, contain much less hornblende and correspondingly larger amounts of chlorite. The feldspar-diorite porphyry is a finer-grained porphyritic phase of the diorite which occurs as dikes.

Although large masses of the diorite are not found in close proximity to Timiskaming sediments, these rocks are cut by dikes of the feldspar-diorite porphyry. Thus, the post-Timiskaming age of the Howey diorite is established.

LATE PRE-ALGOMAN

Quartz porphyry.—The quartz porphyries occur as dikes and as irregular stock-like masses. Their composition is variable, and such names as quartz-feldspar porphyry, granodiorite porphyry, and tonalite porphyry are applicable to different phases. The most common type is a massive, fine-grained, light-weathering rock with rounded quartz grains and small feldspar crystals as phenocrysts. Two analyses presented by E. L. Bruce and J. E. Hawley[6] give an excellent idea of the mineralogical and chemical variations of the porphyry (Table 2). Number 1 is the common acid type and may be correctly termed a "quartz-albite porphyry"; No. 2 is representative of the tonalite type.

Dikes of the quartz-porphyry suite are found cutting the Howey diorite as well as the various Timiskaming and Keewatin formations. The most noteworthy dike showing this relationship contains the ore bodies of the Howey and Hasaga gold mines.

Thin sections of porphyry from the freshest and most massive outcrops in the area show that the rock is regionally altered. All the original hornblende has been altered to chlorite and some of the feldspars to sericite. Although no car-

[6] "Geology of the Basin of Red Lake, District of Kenora (Patricia Portion)," *Ont. Dept. Mines Ann. Rept.*, Vol. XXXVI, Part III (1927), pp. 28, 36.

bonate is shown in the above analyses, it was observed in practically all the sections examined.

Feldspar porphyry.—Feldspar porphyry occurs as dikes in the southeastern quarter of the Red Lake area. It is generally a fine-grained, medium- to light-gray rock with small phenocrysts of albite (An_{95} An_5)and orthoclase. In composition it varies from a granite to an albite granodiorite.

TABLE 2

ANALYSES AND RECAST MINERAL COMPOSITIONS OF QUARTZ PORPHYRIES

Oxide	No. 1	No. 2	Mineral Recast	No. 1	No. 2
SiO_2	75.87	73.90	Quartz	46.87	47.00
Al_2O_3	15.50	12.00	Albite	13.10	20.67
Fe_2O_3	0.81	1.58	Anorthite	.....	8.41
FeO	0.28	4.39	Orthoclase	11.89	3.66
MgO	0.45	1.25	Sericite	19.90	.....
CaO	.....	1.69	Biotite	3.73	8.45
Na_2O	1.55	2.44	Chlorite	3.97	4.03
K_2O	4.03	1.33	Magnetite	.....	1.67
TiO_2	.....	0.84	Ilmenite	.....	1.60
H_2O	1.01	0.65	Pyrite	.....	0.15
			Kaolin (?)	.....	5.29
Total	99.50	100.07	Total	99.46	100.93

Dikes of the rock are found cutting across dikes of the quartz-porphyry suite. Although the later age of the rock is established, for three reasons it is believed to be closely associated in time and probably in origin with the quartz porphyry. First, dikes of the rock often occur in close association with the quartz porphyry in the same zone of weakness. Second, both porphyries show variations toward one another and in some areas are most difficult to map separately. Third, they are texturally and lithologically similar and exhibit the same type of alteration. For these reasons the two formations have been classed together as late pre-Algoman.

ALGOMAN

The seven ages of intrusive rocks, which originated after the feldspar porphyries and quartz porphyries, have been classed as Algoman on grounds of intrusive relationships, lithological characteristics, and degree of alteration.

Granodiorite porphyry.—Granodiorite porphyry or quartz and feldspar porphyry, as it is sometimes termed, occurs as dikes in Heyson and Dome townships. It is a gray rock with abundant phenocrysts of pinkish feldspar and colorless to bluish quartz set in a massive, fine-grained groundmass. The phenocrysts vary from 0.1 to 0.2 inch in diameter, occur in about equal proportions, and make up about 20 per cent of the rock. An estimate of the mineral composition, made by microscopic methods, indicates that the rock is composed of 35 per cent quartz, 50 per cent albite-oligoclase (Ab_{90} An_{10}), 7 per cent orthoclase and microcline, 5 per cent biotite, and about 1 per cent each of sericite, epidote, and magnetite.

A large dike, up to about 1,000 feet wide, which runs in an east-northeast direction across Heyson Township, cuts off small dikes of the quartz porphyry and is definitely later in age. Although its relationship to the feldspar porphyry was not established, it is believed to be later because of the close association of the feldspar porphyry and the quartz porphyry. It has been classed as the oldest formation in the Algoman period not only because of its intrusive relationship to the quartz porphyry but, first, because it is granitic in appearance and composition, and, second, because it is fresh and unaltered, even where in contact with the much more highly altered quartz porphyry. All three factors indicate the plausibility of the classification advanced and indicate a time interval of some magnitude between those formations classed as late pre-Algoman and the granodiorite porphyry.

Dikes of hornblende diorite and hornblende gabbro, which will be described later, were found with intrusive relations to the granodiorite porphyry.

Hybrid granite.—The term "hybrid granite" includes a complex series of rocks which have been produced partly by the replacement and assimilation of greenstones and partly by intrusion. They vary in composition from granitized and recrystallized basalts to diorites, granodiorites, and granites. Much of the rock, especially that formed by replacement of the sheared greenstones, is gneissic. The intrusive portions of the formation are generally fine-grained, massive rocks, but in places they are porphyritic.

The hybrid complex appears to have been developed at an early stage in the main Algoman period of intrusion. As the development of hybrid rocks by granitization processes is known to be associated with later intrusions of granite in other areas where this phenomenon has been studied,[7] it is highly probable that such is the case in Red Lake. In this area, however, the two formations are separated by a diorite-gabbro suite of rocks and by a hornblende-pyroxenite formation. Relationship with the granodiorite porphyry is not known as the two rock types were not found in the same locality. Relationship with the late pre-Algoman quartz porphyry, however, is definite as narrow zones of hybrid were found cutting off porphyry dikes in the northwest corner of Ball Township. Therefore, although the exact age of the hybrid rocks cannot be definitely established, all criteria point to association with rocks classed as Algoman.

Quartz diorite.—The quartz-diorite suite of rocks, which occurs as dikes and as small elongate stocklike masses, includes more basic types such as diorite, hornblende diorite, and hornblende gabbro, and small dikes of feldspar-diorite porphyry and feldspar-gabbro porphyry. The rocks are medium to coarse-grained, grayish-green to grayish-black rocks with variable amounts of quartz, andesine (Ab_{65} An_{35} to Ab_{50} An_{50}), hornblende, biotite, and magnetite. Pyroxene is present in some of the more basic types. In general, the rocks are quite fresh, and the only alteration products are hornblende from the pyroxene; and biotite and chlorite from the hornblende.

Dikes of the diorite suite have intrusive relations to rocks of the hybrid granite complex, to the granodiorite porphyry, and to the late pre-Algoman quartz porphyries. As the diorite is cut by all the later intrusive formations, which will be described below, its exact position in the geological table is definitely established. It is probable that the diorites represent an intermediate basic stage in the Algoman period of magmatic activity and that they were formed by differentiation processes in a main magma chamber with the later granitic rocks.

Hornblende pyroxenite.—Hornblende pyroxenite is an unusual rock in the Red Lake area and has been outlined in detail in only one place, on the McKenzie property in Dome Township. Here it is a dikelike mass that has been traced for 2,000 feet and is from 20 to 180 feet wide. It is a medium to coarse, even-grained rock made up of 64 per cent pyroxene, 25 per cent hornblende, 2 per cent biotite, 6 per cent andesine-labradorite (Ab_{50} An_{50}), 1 per cent quartz, and 2 per cent magnetite. Although there has been minor alteration of the pyroxene to hornblende and biotite, and in one section to chlorite, in general the rock is quite fresh.

[7] Horwood, "Granitization in the Cross Lake Region, Manitoba," *Trans. Roy. Soc. Canada*, Vol. XXX, Sec. IV (3d ser., 1936), pp. 99–117.

The dikelike mass at McKenzie cuts across a small irregular stock of hornblende diorite-hornblende gabbro. The contacts of the dike are most irregular, as many small apophyses extend out into the intruded diorite for short distances. As it is cut by dikes of the later granite suite, its age is definitely established.

Granite.—The granitic suite of rocks is represented principally by granites and granodiorites, but in places, where more basic border phases[8] have been developed, the rock is a quartz diorite in composition. In one section, where the rock has large grains of quartz present, the term "quartz porphyry granite" is applied. The rocks occur as large batholithic masses surrounding the basin of Keewatin and Timiskaming formations, as large and small stocks within the basin, and as dikes. The normal pink granite contains about 18 per cent quartz, 45 per cent orthoclase, 10 per cent microcline, 22 per cent oligoclase, 4 per cent biotite, and 1 per cent magnetite. The dioritic border phases, which represent the basic end of the suite, contain 10 per cent quartz, 2 per cent orthoclase, 72 per cent andesine, 10 per cent biotite, 6 per cent hornblende, and 1 per cent magnetite. Small amounts of chlorite, white mica, and carbonate are also present in some of the specimens examined.

The granitic rocks have intrusive relations to all the formations described above. On the McKenzie and Gold Eagle properties, a stocklike mass cuts across both the hornblende pyroxenite and the hornblende-diorite formations and furnishes definite proof of later origin for the granite suite. On the Madsen property the same relationship between granite and hornblende diorite is clearly exposed. In many places throughout the area granitic rocks have been found cutting the hybrid granites and the late pre-Algoman quartz porphyries.

Pre-vein and post-vein basic dikes.—Pre-vein and post-vein basic dikes are the only known post-granite intrusive formations. They are most abundant in and around bodies of granitic rocks, more especially the small stocks such as the McKenzie-Eagle stock on the northeast side of Mackenzie Island and the Dome stock in the southwest corner of Dome Township. Definite age relations between the granite, the two ages of basic dikes, and the ore deposits have been proved in detailed mapping, both surface and underground, at the McKenzie, Gold Eagle, Cochenour, Red Lake Gold Shore, and Howey gold mines.

The pre-vein dikes are fine- to medium-grained, gray-black rocks with an original composition of a diorite. Owing to alteration, much of which was undoubtedly produced by the solutions responsible for the formation of the ore bodies, they are now made up of variable amounts of biotite, plagioclase, quartz, sericite, carbonate, magnetite, and, in some, chlorite. In certain specimens, the original textures have been almost completely destroyed by the alteration. A dike from the McKenzie Red Lake mine was found to contain about 13 per cent chlorite, 1 per cent biotite, 40 per cent oligoclase-andesine (Ab_{70} An_{30}), 12 per cent quartz, 15 per cent sericite, 16 per cent carbonate, 1 per cent epidote, and 2 per cent magnetite. Chemical analyses and modal mineral recasts of pre-vein and post-vein basic dikes are presented in Table 3.

The post-vein basic dikes are almost identical in appearance, texture, chemical composition, and mineral composition to the pre-vein dikes. Some of them

[8] W. K. Gummer, "Border Rocks of a Granite Batholith, Red Lake, Ontario," *Jour. Geol.*, Vol. XLIX (1941), pp. 641–56.

are slightly lighter in color, owing probably to a larger percentage of plagioclase and a smaller amount of biotite. They are less altered than the pre-vein dikes and in general do not contain as much carbonate or as much sericite. Original hornblende, whose presence in both sets of dikes is indicated by textural criteria, type of alteration, and chemical composition, has been completely altered to biotite or chlorite.

TABLE 3

CHEMICAL ANALYSES AND RECASTS OF PRE-VEIN AND POST-VEIN BASIC DIKES

Oxide	Pre-vein Dike*	Post-vein Dike†	Mineral Recast	Pre-vein Dike*	Post-vein Dike†
SiO_2	49.76	50.95	Quartz	15.57	14.50
Al_2O_3	15.87	17.97	Albite	22.67	28.05
Fe_2O_3	1.36	2.79	Anorthite	5.67	12.02
FeO	4.93	4.82	Orthoclase	4.31	.....
MgO	4.45	3.81	Sericite	18.77	16.54
CaO	5.96	6.51	Biotite	12.71	3.38
Na_2O	2.67	3.30	Chlorite	.....	10.06
K_2O	4.21	2.26	Carbonate	14.16	8.49
H_2O	1.50	2.24	Apatite	1.05	0.77
P_2O_5	0.49	0.35	Magnetite	1.96	4.05
CO_2	6.72	3.89	Ilmenite	2.25	1.87
TiO_2	1.19	0.99	Pyrite	1.27	0.51
MnO	0.18	.....	Unassigned		
FeS_2	1.27	0.51	H_2O	0.17	0.15
Total	100.56	100.39	Total	100.56	100.39

* The pre-vein basic dike is from the 750-foot level, Howey mine. Plagioclase in the pre-vein dike is oligoclase, $Ab_{80}An_{20}$.

† The post-vein basic dike is from the 350-foot level, McKenzie mine. Plagioclase in the post-vein dike is oligoclase-andesine, $Ab_{70}An_{30}$.

Ore deposits.—The ore deposits of the Red Lake area are gold-bearing veins or zones, which may be divided into four types of deposits: (1) quartz veins; (2) fracture zones with quartz stringers; (3) cherty quartz-carbonate zones; and (4) shear zones with disseminated sulphide mineralization. The first type occurs at the McKenzie, Gold Eagle, and old Red Lake Gold Shore mines; the second at the Howey and Hasaga mines; the third at the Cochenour Willans and McMarmac properties; and the fourth at the Madsen mine. At the McKenzie, Gold Eagle, Red Lake Gold Shore, Howey, and Cochenour Willans mines definite age relations between the ore bodies and the basic dikes were obtained. The pre-vein dikes are cut by mineralized bodies such as quartz veins or stringers, or cherty quartz-carbonate zones, whereas the post-vein dikes cut sharply across the ore bodies and have chilled margins. As the relative time of the period of mineralization is definitely established at these mines, it is probable that mineralization at the other properties also comes between the two ages of basic dikes.

HELIUM AGE INVESTIGATIONS

The helium contents of the rocks were determined by fluxing the rock in a high-temperature vacuum furnace. After burning the hydrogen over a palladium catalyst and removing the remainder of the impurities by means of liquid air-cooled charcoal traps, a known portion of the purified helium was compressed and measured in a fine-calibrated capillary tube. The rate of helium production was obtained by determining the rate of emission of alpha rays from thinly deposited rock films of known mass and area.

From the experimental data the helium index, I, is calculated by means of the equation

$$I = \frac{30.65\ He}{a},$$

where He is the quantity of helium determined in units of 10^{-5} cubic centimeters per gram and a is the activity index, expressed as alpha rays per milligram per hour. The figure 30.65 is a conversion factor based on the known rates of production of helium from radioactive elements. If there were no gain or loss of helium, and He were equal to He_0—the total quantity of radiogenic helium produced within the rock since its formation—then I would be equal to the ab-

solute age, say, t_1. For younger rocks, this quantity

$$t_1 = \frac{30.65\ He_0}{a}$$

represents actually the absolute age. Since the figure 30.65 is based on the known rates of production of helium from radioactive elements, a correction factor has to be introduced when dealing with rocks over three hundred million years old. This correction takes care of the decay of the parent radioactive elements during geological time.[9] For such rocks the following equation is applicable:

$$t = t_1 - 6.25 \times 10^{-5} t_1^2 ,$$

where t is the absolute age. The coefficient 6.25×10^{-5} is determined by the known rates of decay of the parent-elements, uranium, actino-uranium, and thorium.

Except in rare cases of contamination by magmatic helium, the experimental quantity He always tends to be less than the total quantity He_0, owing, we believe, to helium leakage. By making corrections based upon helium retentivities[10] and mineral compositions, it is possible to estimate He_0 approximately. The helium content calculated in this way is designated He_2. When He_2 is substituted for He_0 in the above equations, the helium age is designated by t_{1_h} or t_h in place of t_1 and t; for example,

$$t_h = t_{1_h} - 6.25 \times 10^{-5} t_{1_h}^2 .$$

Method used for Red Lake rocks.—In the Red Lake suite of rocks the dominant minerals are hornblende and its alteration products and feldspar. Since hornblende is higher in radioactivity and shows better retentive properties for helium, samples were selected, where possible, from which hornblende concentrates could be obtained by mechanical separation or by means of heavy liquids.

Because of the difficulty in obtaining samples of uniform composition, and with comparable amounts of alteration, and because of other uncertainties, it was not possible to determine directly the relative ages by means of the helium index. It was necessary to bring the results to a nearly comparable basis by correcting, as far as possible, the results on each sample for the effects of variations in composition and degrees of alteration upon the helium retentivity. A complete solution of the problem would involve determinations of the helium content and the radioactivity of each mineral in each sample, mineralogical analyses, determinations of the degree of alteration of each mineral in each sample, and data on the retentive properties of each mineral as a function of alteration and other pertinent factors. After careful consideration of the importance of these factors, in the light of information available at the present time, it was possible to simplify the problem to some extent. For purposes of calculation, the rocks were separated into mafic and felsic portions. Experimental work was confined largely to the mafic portions or to rocks with a high mafic content. However, since some felsic minerals were present in all the samples studied, it was necessary to make corrections for their effect. As the radioactivity of feldspar and quartz, a_f, is usually less than that of the ferromagnesian minerals, a_m, and as the proportion of felsic minerals was generally low, this correction is small. To simplify the experimental procedure, the curve in Figure 1 was used. This curve is based upon

[9] Keevil, "The Calculation of Geological Age," *Amer. Jour. Sci.*, Vol. CCXXXVII (1939), pp. 195–214.

[10] Keevil, "Helium Retentivities of Minerals," *Amer. Geophys. Union Trans. of 1941* (April, 1941), and *Amer. Min.*, Vol. XXVI (1941), pp. 403–4.

a large number of radioactive results on mineral separates which show a tendency to fall near such a curve. For present purposes it is most significant to point out that, at zero concentration, the ratio of mafic to felsic is equal to 1 and that for the Red Lake granodiorite, specimen No. 56, with an activity index of 1.33, the ratio was found to be 2.9. With this curve, values of a_m/a_f were obtained from the experimentally determined activity index. The relative amounts of felsic, f, and mafic, m, portions in the samples were determined microscopically.

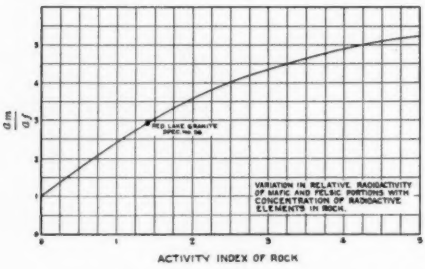
RED LAKE GRANITE
SPEC. NO. 56
VARIATION IN RELATIVE RADIOACTIVITY OF MAFIC AND FELSIC PORTIONS WITH CONCENTRATION OF RADIOACTIVE ELEMENTS IN ROCK
ACTIVITY INDEX OF ROCK

FIG. 1.—Curve used for approximating relative radioactivities of mafic and felsic portions of rocks.

With values for the retentive properties of the felsic, Rf, and mafic, Rm, portions, it was possible to calculate the helium age by means of the equations[11]

$$t_{1_h} = \frac{I}{\dfrac{Rf(f)}{1+m\left(\dfrac{a_m}{a_f}-1\right)} + \dfrac{Rm(m)}{m+\dfrac{a_f}{a_m}(1-m)}} = \frac{I}{C} = \frac{He_2}{a}$$

and

$$t_h = t_{1_h} - 6.25\,(10^{-5})\,t_{1_h}^2 .$$

Estimation of retentive factors.—Theoretical considerations have indicated the nature of the laws governing the retentive forces of crystal structures and the diffusion of helium within such structures.[12] From both theoretical and experimental results, it is apparent that minerals with close-packed structures retain most of their radiogenic helium during geological time, even though they may be slightly altered and strained. However, with excessive alteration and the formation of secondary minerals and structures, it has been found that much of the helium is lost. In some cases, such as in highly altered feldspars, this loss has been as high as 95 per cent. In the best cases it is estimated from both theoretical and experimental results that about 95 per cent of the helium is retained.

From such considerations, it is now believed that the effect of minor alteration is slight but that, once the structure of the mineral has become disrupted, the retentive qualities decrease rapidly. In the secondary minerals produced by the alteration, only from 2 to 10 per cent of the original radiogenic helium may be present. The effects of alteration also seem to vary somewhat in different minerals. The general trends of the curves assumed for the effect of alteration upon retentivity of pre-Cambrian hornblende and feldspars are shown in Figure 2. In younger rocks studied previously there is some evidence that the curves are displaced upward. The somewhat greater loss of helium for Red Lake rocks may be due to the presence of other leakage factors which have been grouped under alteration.

In locating the actual positions of the curves shown in Figure 2, the results obtained from two groups of specimens

[11] A mean helium age may also be calculated by using eqs. 34*a* and 34*b* in Keevil, "The Calculation . . . . ," *op. cit.*

[12] Keevil, "Interatomic Forces and Helium in Rocks," *Proc. Amer. Acad. Arts and Sci.*, Vol. LXXIII, No. 11 (1940), pp. 311–59.

from the vicinity of McKenzie Red Lake mine were used. Two samples of granodiorite, Nos. 56 and 57, and two specimens of hornblende diorite, Nos. 61 and 62, showed considerable differences in the relative amounts of alteration and afforded valuable data on the helium-retentivity curves. Minerals other than hornblende and feldspar were taken into account and grouped with the mafic or the felsic portions. The degree of alteration was obtained by estimating the percentages of good crystal and altered crystal in a large number of fields in thin sections of the rocks.

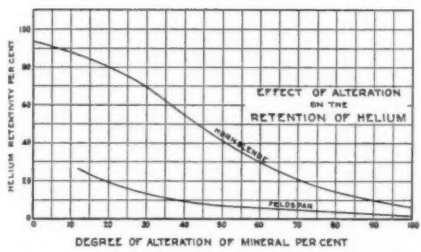
HELIUM RETENTIVITY PER CENT
EFFECT OF ALTERATION ON THE RETENTION OF HELIUM
HORNBLENDE
FELDSPAR
DEGREE OF ALTERATION OF MINERAL PER CENT

FIG. 2.—Curve used for obtaining helium retentivities from estimations of degree of alteration.

The standard basis for calculating *Rm* and *Rf*, the helium retentivities of the mafic and felsic portions of the samples, was the table of values presented in Table 4. The same procedure was followed for every rock studied. The compositions used are listed in Table 5. A test of the method applied to duplicate specimens of granodiorite and hornblende diorite is given in Table 6.

Results of method.—The results of fifteen "helium age" determinations, using the method of correction described above, are given in Table 7. One determination, obviously contaminated by extraneous helium, is not included. Although they show variations, these are within the limits of probable error and the average ages are in good agreement, considering the wide variations in the compositions and textures of the rocks. The results also provide good evidence for the theory that low helium-index values are due to loss of helium by alteration and disruption of crystal structures, and also, in this suite of rocks, for the validity of the method of correcting for helium leakage on the basis of degree of alteration.

TABLE 4

HELIUM RETENTIVITY VALUES USED IN HELIUM AGE CALCULATIONS

Mineral	Degree of Alteration (Fractional)	Helium Retention (Per Cent)
Pyroxene....	1/3	72
Hornblende..	0	93
Hornblende..	1/4	75
Hornblende..	1/2	40
Hornblende..	3/4	16
Hornblende..	1	6
Hornblende..	Secondary	15
Biotite.....	Secondary	10
Chlorite.....	Secondary	6
Chlorite.....	Disseminated secondary	3
Magnetite...	Primary	95
Magnetite...	Secondary	50
Felsic minerals.	Slightly altered	15
Felsic minerals.	1/3 to 2/3 altered	5
Felsic minerals.	Highly altered	2

The results are also important from the standpoint of correlation of the Red Lake intrusive rocks. Although empirical alteration curves and approximate values for the helium retentivities of the various minerals are used,[13] the same values and procedures were used for each rock. Therefore, although these data are only approximations, the results are on a comparable basis and the helium ages may not be far from the absolute ages (i.e., within the limits of probable error). Those samples showing the smallest differences in helium retentivities provide the most useful data; those in which the

[13] *Ibid.*

TABLE 5

MINERAL COMPOSITIONS OF ROCKS USED FOR HELIUM AGE DETERMINATIONS IN WEIGHT PER CENT

MINERALS	SPECIMEN NUMBERS														
	71	72	19	20	20A	56	57	66	61	62	139	139H	24	144	144H
Femic	36	25	69	83	60	53	47	90	87	55	20	45	44	45	47
Hornblende (original)															
Fresh	....	....	11	18	13	2	2	10	14	....	....	....	....	....	....
1/4 altered	....	....	10	8	6	15	8	6.5	23	0.5	....	....	....	1	1
1/2 altered	....	....	2	2	1	20	7	6.5	35	1	....	....	....	1	2
3/4 altered	....	....	....	....	....	15	14	2	13	5.5	....	....	....	2	2
Chlorite	31	20	....	....	....	1	16	....	2	48	20	45	40	41	42
Secondary	....	....	46	55	40	....	....	....	....	....	....	....	....	....	....
Biotite	3	3	....	....	....	....	....	1	....	....	....	....	3.5	....	....
Pyroxene	....	....	....	....	....	....	....	63	....	....	....	....	....	....	....
Magnetite	2	2	....	....	....	....	....	1	....	....	....	....	0.5	....	....
Felsic	64	75	31	17	40	47	53	10	13	45	80	55	56	55	53
Feldspar, etc.	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Slightly altered	30	30	6	10	20	24	25	10	13	10	2	2	10	8	8
1/3–2/3 altered	34	45	25	7	20	23	28	....	....	30	58	38	15	27	27
Highly altered	....	....	....	....	....	....	....	....	....	5	20	15	31	20	18

hornblende is altered to chlorite may be in error up to about 50 per cent.

Helium age results and Red Lake geochronology.—The position of the Red Lake intrusive rocks in the geological time scale has been determined approximately by the helium method. On the basis of helium-index determinations alone, without correcting for helium leakage, it was found that the hornblende diorite of specimen No. 61 is older than 1,060 million years. This determination suggests that the diorite is pre-Keweenawan and probably Algoman in age. Thus all intrusive formations of earlier origin are Algoman or pre-Algoman. One of the post-granite basic dikes, specimen No. 20, had a helium index of 510, higher than that for any North American Keweenawan rock. Therefore, it is unlikely that any of these dikes are as young as Keweenawan. All data, both geological and geophysical, strongly indicate that the basic dikes, the granite and granodiorite, the hornblende pyroxenite, and the diorites are all of Algoman age.

On the basis of more detailed calculations of helium ages, presented in the last column of Table 7, the rocks fall into an older group, with an age of about 1,760 million years, and a younger group, with an age of about 1,350 million years. A possible intermediate group, of about 1,490 million years, is also indicated.

TABLE 6

TEST OF METHOD OF CORRECTING FOR HELIUM LEAKAGE

ROCK	SPEC. NO.	DEGREE OF ALTERATION	RETENTION FACTOR FOR HORNBLENDE	
			Calculated from Retentivities and Microscopic Data	Obtained from Experimental Data (Using t = 1,300)
Granodiorite	56	Slightly altered	0.44	0.43
	57	More altered	.30	.29
Hornblende diorite	61	Slightly altered	.65	.80
	62	Highly altered	0.07	0.06

TABLE 7

HELIUM RADIOACTIVITY DATA FOR ROCKS FROM RED LAKE

Specimen Number	Description	a	a_m/a_f	m	Rm	Rf	I	c	t_{1h}	t_h
71R....	Post-vein basic dike (McKenzie mine)	0.87	2.2	36	0.09	0.09	131	0.09	1,440	1,320
72R....	Pre-vein basic dike (McKenzie mine)	0.99	2.2	25	0.09	0.09	135	0.09	1,500	1,370
19*....	Pre-vein quartz diorite dike (Cole mine)	0.189	1	69	0.29	0.07	244	0.22	1,110	1,040
20.....	Pre-vein quartz diorite dike (Cole mine)	0.33	1	83	0.38	0.1	510	0.333	1,530	1,390
20A†...	Pre-vein quartz diorite dike (Cole mine); mineral selection from rejects No. 20	0.098	1	60	0.38	0.1	230	0.268	860	810
56.....	Basic border phase of granodiorite (McKenzie mine)	1.33	2.9	53	0.44	0.1	502	0.361	1,390	1,280
57.....	Basic border phase of granodiorite (McKenzie mine)	0.817	2.0	47	0.30	0.1	315	0.228	1,380	1,270
66.....	Hornblende pyroxenite (McKenzie mine)	0.404	1.5	90	0.72	0.15	985	0.66	1,490	1,360
61.....	Hornblende diorite (McKenzie mine)	0.445	2.0	87	0.59	0.15	1,060	0.65	1,630	1,470
62.....	Hornblende diorite (McKenzie mine)	1.46	3	55	0.06	0.05	79	0.058	1,360	1,250
139R....	Tonalite porphyry (Howey property)	2.17	3.5	20	0.03	0.044	49	0.037	1,325	1,230
139H....	Tonalite porphyry (Howey property), heavy-liquid separate	2.40	4.0	45	0.03	0.045	56	0.034	1,648	1,490
24R....	Howey diorite (Howey property east)	0.635	2	44	0.07	0.05	104	0.062	1,680	1,510
144R....	Howey diorite (Howey property, Lornow L)	0.91	2.5	45	0.09	0.05	151	0.077	1,960	1,730
144H....	Howey diorite (Howey property, Lornow L), heavy-liquid separate	0.87	2.3	47	0.09	0.05	154	0.077	2,000	1,760

* Weathered surface specimen.

† Second selection of hornblende-rich grains.

NOTE.—R = Rock used in determinations, no femic mineral separate possible. H = Hornblende concentrate by heavy-liquid separation used in determinations. In other specimens a hornblende concentrate by mechanical selection was used.

a = Activity index, alpha particles per milligram per hour

a_m/a_f = Relative activities of femic (a_m) and felsic (a_f) portions of rock

m = Percentage of femic minerals in sample used for age determinations

Rm = Helium retentivity of the femic portion of sample

Rf = Helium retentivity of felsic portion of sample

I = Helium index calculated by substituting experimental values for helium and radioactivity into age equation

c = Correction factor based on helium retentivities and upon mineral composition and degree of alteration as determined microscopically

t_{1h} = Helium age in millions of years calculated without considering decay of parent radioactive elements

t_h = Helium age in millions of years corrected for the effect of decay of uranium, actino-uranium, and thorium

However, because of the magnitude of the probable error, it is not possible to state definitely that there are three periods of magmatic activity. The term "Algoman," as indicated in Table 8, where other age determinations are outlined, may be applicable for rocks of considerable age difference. In the Red Lake area it was used in the more restricted sense. It is possible that the correction factors applied for helium leakage may have been rather extreme. If such is the case, the absolute ages would be slightly lower than shown.

TABLE 8

APPROXIMATE PRE-CAMBRIAN TIME SCALE

Other Age Determinations		Geological Division	Red Lake Helium Age Determinations	
Age in Millions of Years	Rock Formation		Rock Formation	Age in Millions of Years
500	Swedish Kolm Keweenawan diabases	Keweenawan		500
	Norwegian cleveite Wilberforce uraninite			
1,000	Swedish magnetite Ontario magnetite from Hart Township			1,000
			Basic dikes Granodiorite Hornblende pyroxenite Diorite, etc.	
	Moose Mountain garnet	Algoman		
1,500	South Dakota uraninite		Tonalite porphyry	1,500
	Yellowknife granite*			
	Russian uraninite	Early pre-Cambrian	Howey diorite	
	Manitoba uraninite			
2,000	Stillwater norite, Montana* Manitoba pillow lava*			2,000

* Corrected helium ages.

With the exception of the two granodiorite specimens, Nos. 56 and 57, and one specimen excluded because of extraneous helium, the average helium ages fall in or close to the order of the geological sequence. The discrepancies are with-

in the limits of experimental error, but these anomalies may possibly be due to the coarser-grained textures of the rocks. Although the errors are appreciable, the general trend of the results roughly corroborates the relationships and groupings indicated by field work and shows some promise for the method of correcting helium indices by means of retentivity data.

Helium age results and relationship of ore deposits.—Age determinations on the pre-vein and post-vein basic dikes and on the granodiorites cut by these dikes furnished information that is in accord with theories based on field evidence. From the similarities in appearance, texture, mineral and chemical composition, and locus of occurrence, it was believed that the pre-vein and post-vein basic dikes are closely associated in age and probably genesis. Because these dikes are found principally in and near intrusive stocks of granite and granodiorite, and because they contain the same minerals, it was thought that they represent the last stages in the period of magmatic activity that produced the granite, and, therefore, are genetically associated with the granite. Helium work on the dikes showed that they have almost identical radioactivity constants and almost identical helium indices and comparable helium ages as calculated from tentative retentivity curves. These data support the genetic theory based on field evidence. The similarity between the helium ages of the dikes and the granitic rocks also affords corroborative data for the association suggested by field work. As some of the ore deposits were formed in the interval between the times of formation of the two ages of basic dikes, a close genetic relationship between ore bodies and basic dikes seems probable. If these dikes are genetically associated with the granites, then the ore deposits are also similarly associated.

SUMMARY AND CONCLUSIONS

Detailed geological work in the Red Lake area has shown that there are ten ages of intrusive rocks in the area and has indicated that these ten ages may be grouped into three periods of magmatic activity: early pre-Algoman, late pre-Algoman, and Algoman. It has also indicated that two ages of post-granite basic dikes and the ore deposits of the area are genetically related, both to one another, and to the earlier granite.

Helium age determinations have furnished corroborative data and have indicated that the intrusive formations can be divided into two, and possibly three, periods of magmatic activity. They have also suggested a close relationship in time and possibly in origin between the two ages of basic dikes and between the dikes and the granite. This would make the ore deposits closely related in time and probably in origin to both basic dikes and granite.

Data obtained from field geology, from microscopic work on thin sections and mineral concentrates, and from helium age determinations in which the mineral content and degree of alteration were considered have been combined for the first time to afford evidence on the relationship between different intrusive formations and on the relationship between igneous rocks and ore deposits. This preliminary treatment is believed to be sufficiently encouraging to warrant further research along this line.

The genetic relationship indicated between the ore deposits, the basic dikes, and the granitic rocks suggests that the

most favorable prospecting areas lie in the vicinity of granite masses, particularly around stocklike bodies where basic dikes are common. The actual position of any deposit will depend on the presence of suitable structures.

The writers hope that this new approach to problems of correlation, petrogenesis, and ore genesis may be developed to the point where it will find application in the fields of both scientific and economic geology.

WESTWARD EXTENSION OF THE KANSAS "EQUUS BEDS"[1]

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ABSTRACT

A well-developed early Pleistocene terrace which extends along the valley of the Smoky Hill River through Ellis, Russell, and Ellsworth counties, Kansas, is described. An abandoned high-level valley—the Wilson Valley—which carried the drainage of the early Pleistocene upper Saline River, enters the Smoky Hill Valley at the high-terrace level in northwestern Ellsworth County. Several invertebrate faunules and associated vertebrate remains are listed from these Pleistocene deposits. On the basis of physiographic data the terrace deposits and the sediments underlying the floor of Wilson Valley are considered as equivalent, in part, to the McPherson formation (restricted) of the "Equus beds" area of central Kansas. The described terraces and abandoned valley constitute new data pertaining to the Pleistocene drainage history of central and northern Kansas.

INTRODUCTION

Terrace deposits of presumed Pleistocene age were noted a number of years ago along the valleys of Smoky Hill and Saline rivers in Russell[2] and Ellis[3] counties, Kansas. Earlier, W. N. Logan[4] had described from this area gravel beds which he believed to be younger than the "Tertiary grit" (Ogallala formation) and referred to them as the "Salt Creek gravel beds." During the season of 1941 Frye was engaged in a study of the ground-water resources of parts of Russell and Ellis counties. This work offered an opportunity to study the terraces along the Smoky Hill Valley through these counties and farther east in Ellsworth County and to make some observations of the terrace deposits along the Saline Valley. The ground-water investigation was a co-operative study by the United States Geological Survey, the Kansas State Geological Survey, and the Division of Sanitation of the Kansas State Board of Health and was under the immediate supervision of S. W. Lohman. In September, 1941, the writers spent several days in the area in joint field work, during which time Hibbard and Leonard collected many fossils. The following discussions of physiography and stratigraphy are by Frye, the description of the snail faunas is by Leonard, and description of the vertebrate fossils is by Hibbard.

PHYSIOGRAPHY

Erasmus Haworth and J. W. Beede,[5] in their discussion of the "Equus beds" area and the McPherson formation, presented evidence that the McPherson formation was fluviatile in origin. They discarded the idea of deposition of the McPherson sediments by a through-flowing stream, however, because the upper surface of the deposits along the "McPherson ridge" was at too great an altitude to have been formed by a south-flowing stream, and they knew of no terraces along the Smoky Hill Valley that

[1] Published with the permission of the director of the Geological Survey, U.S. Department of the Interior, and the director of the Kansas State Geological Survey.

[2] W. W. Rubey and N. W. Bass, "The Geology of Russell County, Kansas," *Kan. Geol. Surv. Bull. 10* (1925), pp. 19–25.

[3] N. W. Bass, "Geology of Ellis County," *Kan. Geol. Surv. Bull. 11* (1926), pp. 16–18.

[4] "The Upper Cretaceous," *Kan. Univ. Geol. Surv.*, Vol. II (1897), pp. 218–19.

[5] "The McPherson Equus Beds," *Kan. Univ. Geol. Surv.*, Vol. II (1897), pp. 287–96.

were consistent with such a history. The first of these two objections was nullified when it was discovered that the uppermost 100 feet of the deposits overlying the stream-laid sands under the "McPherson ridge" consist of eolian loess,[6] and now the mapping of Pleistocene terraces, shown in Figure 1, along Smoky Hill Valley eastward to the western boundary of McPherson County, seems to remove the other objection. The presence of the "Wilson Valley" (to be described later), through which the upper Saline drainage formerly entered the Smoky Hill Valley in western Ellsworth County, explains the seemingly anomalous course of the lower Saline Valley with respect to the McPherson channel. Thus it seems that the Smoky Hill Valley offers the key to the interpretation of the Pleistocene history of much of central and north-central Kansas.

Bedrock Stratigraphy

The rocks underlying the Ellis-Russell-Ellsworth area consist of the Ninnescah shale,[7] of Permian age, and the "Dakota group," Graneros shale, Greenhorn limestone, Carlile shale, and Niobrara chalk of Cretaceous age. These rocks dip gently westward, although local dips in any direction may be encountered. The strata consist of shale, limestone, and sandstone, each of which shows varying degrees of resistance to erosion. Although the various stratigraphic units may have influenced the width of the valley, they have exerted little or no control on the gradient of the major terrace. This is indicated by the generalized cross section (Fig. 1), which shows the base of the Greenhorn limestone and gradients of the upper, prominent terrace and flood plain of the Smoky Hill River.

The Cretaceous rocks under much of the divide areas in central and western Russell County and in Ellis County are overlain by a veneer of sand and silt. The Fort Hays limestone member (lower part of the Niobrara chalk) forms a prominent east- and south-facing escarpment in eastern Ellis County, and on the upland west of this escarpment Bass[8] has described deposits that are considered by him to be equivalent to the Ogallala formation of Nebraska and western Kansas. East of the Fort Hays escarpment the upland surface is underlain by Carlile shale and Greenhorn limestone. In eastern Ellis County and western Russell County most of this surface is mantled by a thin veneer of silt and sand which ranges up to 40 feet in thickness. Locally the silt and sand contain abundant caliche. These deposits are probably younger than the Ogallala formation of central Ellis County and are certainly older than the high-terrace deposits along the Smoky Hill Valley.

Topography and Characteristics of Terraces

The uppermost terrace along the Smoky Hill Valley is clearly recognizable. In many parts of the area its upper surface is relatively flat and undissected, and at the Russell-Ellis county line this surface is about 75 feet above the flood plain and 100 feet below the upland. The width of the bedrock valley at the high-terrace level is about 2 miles. The height of the high terrace above the flood

[6] John C. Frye, "Physiographic Significance of Loess near McPherson, Kansas," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XXIII (1939), pp. 1232–33; S. W. Lohman and John C. Frye, "Geology and Ground-Water Resources of the 'Equus Beds' Area of South-Central Kansas," *Econ. Geol.*, Vol. XXXV (1940), pp. 839–66.

[7] G. H. Norton, "Permian Redbeds of Kansas," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XXIII (1939), pp. 1767–74.

[8] *Op. cit.*, pp. 18–20.

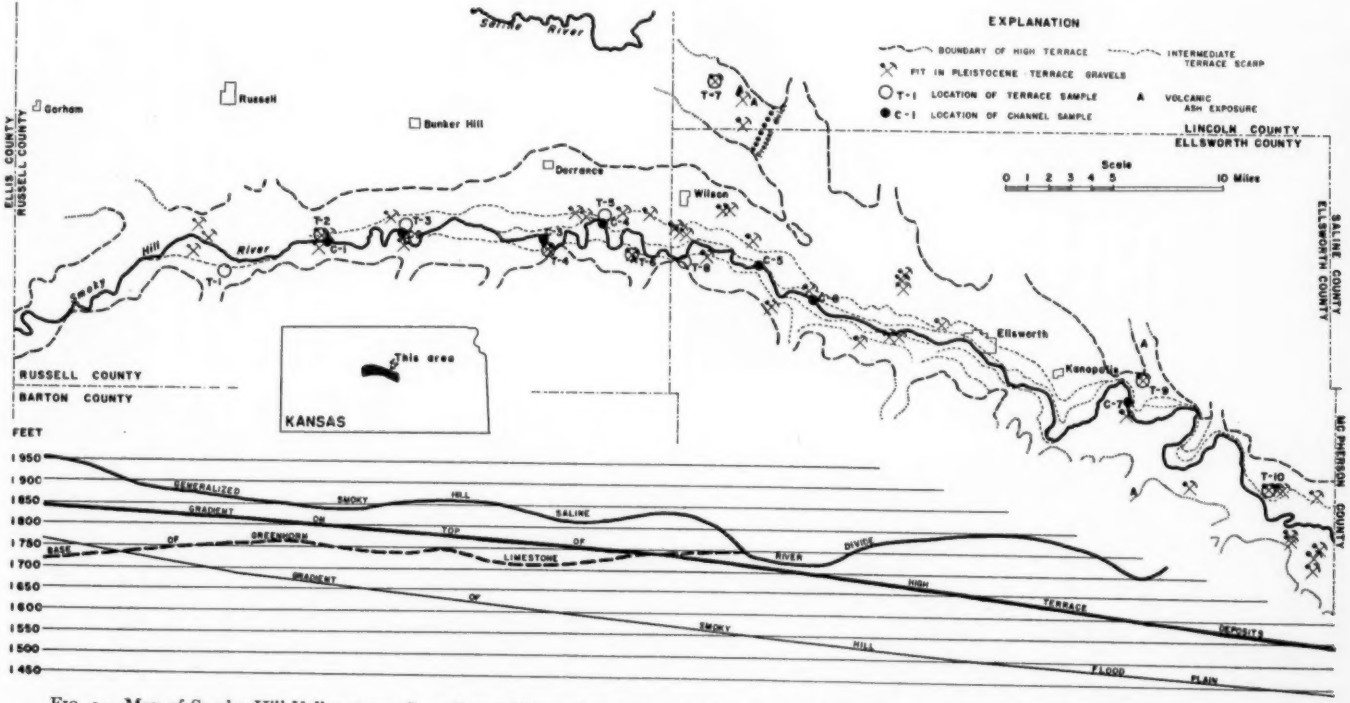

FIG. 1.—Map of Smoky Hill Valley across Russell and Ellsworth counties, showing terraces, location of gravel pits, location of sample points, and "Wilson Valley." Small insert shows location of this area within the state of Kansas. Profiles show the gradients on top of the high-terrace deposits and the flood plain of the Smoky Hill Valley, generalized Smoky Hill–Saline River divide, and the base of the Greenhorn limestone.

plain gradually increases eastward, reaching a maximum of nearly 150 feet a few miles east of the Russell-Ellsworth county line. Here the valley attains a maximum width of 6 miles. Farther east in Ellsworth County the valley narrows slightly, and the height of the high terrace above the flood plain decreases to about 100 feet at the Ellsworth-McPherson county line. If the gradient of the high terrace is projected across Ellsworth County, it is found to intersect the top of the channel deposits of the McPherson formation (restricted), which occur less than 20 miles to the southeast.

The high terrace, where well preserved, is characterized by a nearly flat upper surface, underlain by 20–75 feet of gravel, sand, and silt. The boundary between the high-terrace surface and outer slopes of the valley is not sharp, except where it has been accentuated by recent erosion, but is marked by a gently sloping surface that rises to the upland level (Fig. 2). This slope shows bedrock along road cuts and gulleys. The streamward margins of the terrace are marked by distinct scarps in most places. Their height ranges from 30 to 90 feet, depending on whether the ascent is directly from the flood plain or from an intermediate terrace level. The best exposures of the terrace deposits occur along these scarps.

In some localities a special type of scarp recession is shown. That is, the unconsolidated terrace deposits have been eroded back faster than the underlying bedrock, where the bedrock consists of Cretaceous sandstone, and a double scarp has developed. In such cases the upper part of the scarp is developed in loose gravel, sand, and silt, bordered by a narrow rock bench, and the lower part of the scarp descends to an intermediate terrace surface or to the flood plain.

Remnants of a clearly marked intermediate terrace occur locally in western Russell County (Fig. 1), and these become more numerous and persistent in the eastern part of the county. In western and central Ellsworth County the intermediate terrace is well developed, and a still lower terrace becomes recognizable. In eastern Ellsworth County, where the high terrace has been much more extensively dissected by erosion, the intermediate terrace surfaces are wider and more prominent. On the south side of the valley the high terrace is indistinct.

FIG. 2.—High-terrace surface and south valley wall, south side of Smoky Hill Valley, east of the Russell-Ellis county line.

Across the entire area the flood plain of the Smoky Hill River is narrow. In Russell County it does not equal a quarter of a mile in width, and it exceeds this width only slightly in parts of eastern Ellsworth County.

WILSON VALLEY

Although many of the tributary valleys of the Smoky Hill in Russell and Ellsworth counties contain remnants of the high terrace, only one of these seems to be of special significance. A major tributary valley enters the Smoky Hill Valley east of Wilson, at the level of the high terrace (Fig. 1). This high-level valley extends northwest from the Smoky Hill River across northwestern Ellsworth County and southwestern Lincoln County into Russell County. The pres-

ent Smoky Hill–Saline River divide crosses this old valley a few miles north-northeast of Wilson. The high-level valley is traced to the south rim of the Saline River Valley in eastern Russell County, but no remnants of a high terrace are found along the lower Saline Valley. They have been obliterated by erosion. The high-level valley that has been described is appropriately designated the "Wilson Valley," inasmuch as it is especially well preserved near Wilson.

The floor of the Wilson Valley is underlain by gravel, sand, and silt, and locally by volcanic ash, and is continuous with the upper surface of the high terrace east of Wilson. Owing to the fact that the Saline River is more deeply entrenched than the Smoky Hill directly opposite and that its valley is only about half as wide, the high terrace has been nearly completely destroyed in this part of the Saline Valley. The terrace deposits noted along the Saline Valley by Logan,[9] Rubey and Bass,[10] and Bass[11] nearly all occur at a much lower altitude, and, since their upper surface is at a lower altitude than the bedrock floor of the Wilson Valley, they must be younger in age and have been deposited by the Saline after it had left the Wilson Valley and occupied its present course toward the east.

The available data clearly indicate that the early Pleistocene upper Saline River drainage flowed through the Wilson Valley and joined the Smoky Hill River a few miles east of Wilson. This is indicated by the following facts: (1) the floor of Wilson Valley is continuous with the upper surface of the high terrace; (2) it joins the Smoky Hill River Valley with an acute angle upstream; (3) Hell Creek, which drains the northern part of Wilson Valley, joins the Saline River with an obtuse angle upstream, and the tributaries to Hell Creek are barbed with respect to Hell Creek; (4) the Pleistocene deposits underlying the floor of Wilson Valley are lithologically indistinguishable from the deposits of the high terrace; (5) the Wilson Valley faunule is very similar to the Tobin faunule of the high terrace; and (6) the drainage pattern is consistent with such an interpretation.

[9] *Op. cit.* [10] *Op. cit.* [11] *Op. cit.*

Lithology of the Terrace Deposits

The high-terrace deposits, both along the Smoky Hill and in the Wilson Valley, generally consist of gravel at the base and of sand and silt in the upper part. A section (Fig. 3) measured along the scarp at the north side of Smoky Hill River, southeast of Dorrance, is given in Table 1.

Fig. 3.—Exposure of terrace gravel, sand, and silt overlying Cretaceous shales and sandstone, north side of Smoky Hill River, NW. ¼ Sec. 27, T. 14 S., R. 11 W., Russell County.

Another section, which shows a horizon from which snails were collected, was measured on the south side of the Smoky Hill River, a few miles west of the Russell-Ellsworth county line (Table 2).

A section of the deposits underlying the floor of Wilson Valley was measured in southwestern Lincoln County, south of the Saline River, in the headwaters of Hell Creek (Table 3).

On the basis of lithology and source area the terrace sands and gravels may be classed in two general groups: (1) sands and gravels that consist dominantly of igneous material and so represent sediments transported by a through-flowing stream from the Rocky Mountain area or that were eroded from upland

TABLE 1

SECTION MEASURED IN NW. ¼ SEC. 27, T. 14 S., R. 11 W., RUSSELL COUNTY

	Feet
QUATERNARY	
3. Sand and silt, thin-bedded and locally cross-bedded, containing isolated nodules and nodular bands of caliche, buff to tan, grading upward near top into brown, locally dark brown. Lenses of clay, vertebrate fragments, and invertebrate fossils occur near the base. Prairie dog zone 2–4 feet from base	31.8
2. Sand and gravel, interbedded and cross-bedded; a few zones cemented by calcium carbonate; gravel composed of abraded Tertiary and Cretaceous rocks, granite and chert pebbles, and a small per cent of other igneous rocks. Vertebrate fossil fragments, invertebrate fossils, and lenses of clay occur near the top	13.7
CRETACEOUS	
1. Shale and siltstone of the Dakota group, to stream level in Smoky Hill River	35.0

Tertiary deposits west of this area; and (2) sands and gravels that consist dominantly of material derived from near-by Cretaceous rocks. The latter type commonly occurs along tributaries of the Smoky Hill and Wilson valleys and along the margins of the major valley downstream from entering valleys.

A similar distinction of the silts as to mode of origin cannot be made. The upper silt deposits, regardless of the nature of the underlying gravels, are moderately well sorted in most places. They have a tan color and are thin-bedded to massive. Locally silt that is quite distinct from the widespread upper silt occurs interbedded with or above the basal gravels or below volcanic ash. These lower silts are mostly dove-gray to blue-gray in color and more poorly sorted than the upper silts. Also, they contain a higher percentage of clay. It is from these beds that most of the snails listed in this paper have been collected.

TABLE 2

SECTION MEASURED IN SEC. 35, T. 14 S., R. 11 W., RUSSELL COUNTY

	Feet
QUATERNARY	
6. Sand, silt, and gravel. Irregularly bedded, poorly sorted gravel at base, composed dominantly of abraded Cretaceous rocks, interbedded with sand, silt, and clay, becoming finer upward. Upper part tan to brown sand and silt, irregularly bedded to massive, with bands of caliche nodules. Upper part of interval partly covered	20.0
5. Sand, fine, and silt, thin- and even-bedded with lenses of sand, tan to buff. Contains vertebrate fragments and a few invertebrates throughout	10.6
4. Volcanic ash (in a distance of 50 yards westward, thickness increases to 2 feet)	0.2
3. Silt and fine sand, gray to greenish-gray with thin beds of sandy clay. Terrestrial snails occur in the basal 5.5 feet, aquatic snails occur in the upper 1 foot, just below ash (Tobin faunule)	6.5
2. Sand and gravel, cross-bedded, interbedded with thin lenses of silt and zones of abraded Cretaceous limestone pebbles. Cobbles up to 0.7 feet in diameter. Vertebrate fragments	3.9
CRETACEOUS	
1. Shale and siltstone of the Dakota group, to level of Smoky Hill River flood plain	40.0

A series of samples was collected across the area in an attempt to determine whether significant differences exist be-

tween the terrace gravels and the present channel deposits of the Smoky Hill River. The mechanical composition of these samples was determined by sieve analysis. The arithmetic mean size and the arithmetic mean standard deviation of twenty-four channel and terrace samples

TABLE 3

SECTION MEASURED IN SEC. 28, T. 13 S., R. 10 W., LINCOLN COUNTY

	Feet
QUATERNARY	
3. Sand, fine, thin-bedded to laminated, grades upward into massive silt and fine sand, less sandy toward top, tan to reddish buff. Caliche nodules are distributed throughout the upper half	27
2. Volcanic ash, thin-bedded; upper part interbedded with fine sand. Upper part of interval partly covered	7
1. Sand and silt, gray, grading upward into gray sandy, silty clay. Upper 18 inches contain rich molluscan fauna (Wilson Valley faunule). Rodent fragments, amphibian vertebrae, and remains of *Sorex*. Base of section at creek level	11

are indicated in Table 4. The average mean of the channel samples is 2.06 millimeters, whereas that of the terrace samples is 3.12 millimeters, and the range of mean size of the channel samples is 3.37 millimeters, whereas the range of the terrace samples is 8.78 millimeters. Also, the average standard deviation of the channel samples, which may be taken as a measure of sorting as to size, is 2.27 millimeters and that of the terrace samples is 3.70 millimeters. The range in standard deviation is even more striking—4.94 millimeters in the case of the channel samples and 11.73 millimeters in that of the terrace samples. An additional point is that the average permeability of the channel gravels is higher than the average of the terrace samples, although the maximum permeability obtained from the terrace samples exceeds that of any channel sample. From these data it is evident that the terrace gravels are somewhat coarser and less well sorted than the channel deposits of the present Smoky Hill River. This may have been due to greater average current velocity and a larger volume of water and sediment supplied by melting mountain glaciers in the Rocky Mountain region,

TABLE 4

SIZE ANALYSIS OF CHANNEL AND TERRACE SAMPLES

Channel Samples			Terrace Samples		
No. (See Fig. 1 for Locations)	Arithmetic Mean Size (Mm.)	Arithmetic Mean Standard Deviation (Mm.)	No. (See Fig. 1 for Locations)	Arithmetic Mean Size (Mm.)	Arithmetic Mean Standard Deviation (Mm.)
C—1*b*	2.27	2.41	T—1	0.73	0.48
C—1*c*	0.95	0.72	T—2*a*	3.49	6.85
C—2*a*	2.34	2.59	T—3	9.02	9.10
C—2*c*	1.43	2.93	T—4*a*	0.47	0.57
C—3*a*	2.69	2.98	T—4*b*	7.78	11.90
C—3*b*	0.99	0.73	T—5*a*	1.91	2.13
C—4*b*	3.40	5.20	T—7*a*	2.03	2.42
C—5*a*	3.28	4.18	T—8*a*	2.99	3.31
C—5*c*	0.70	0.26	T—8*b*	1.90	2.10
C—6*a*	1.51	1.19	T—9	1.29	1.47
C—6*b*	4.07	3.10	T—10*a*	5.56	3.38
C—7*b*	1.05	0.96	T—10*b*	0.24	0.17
Average	2.06	2.27	Average	3.12	3.70

and/or to a greater rainfall over the drainage basin than at present. It is certain that the terrace materials were deposited by a stream flowing through a broad valley, under much the same conditions as those now existing in the Smoky Hill Valley. The gradient seemingly remained about the same (Fig. 1) throughout the Pleistocene.

Rubey and Bass[12] described the presence of igneous material in these gravels. They believed them to be of Pleistocene age, probably equivalent to the McPherson formation, but were at loss to explain the seeming inconsistence in lithology. Haworth and Beede[13] had stated earlier

[12] *Op. cit.* [13] *Op. cit.*

that the McPherson formation contains no feldspar or granite pebbles but is composed almost entirely of re-worked Cretaceous and Permian rocks. Recent studies,[14] however, have shown that among Cenozoic deposits of the "Equus beds" area the absence of igneous pebbles is characteristic only of the Emma Creek formation, of Pliocene age, and that the McPherson formation (restricted), of Pleistocene age, contains igneous-rock pebbles. The lithology of the Smoky Hill high-terrace gravels is, therefore, similar to that of the McPherson formation (restricted). Inasmuch as the gradient of the high-terrace deposits, when projected, conforms closely with the altitude and gradient of the top of the channel deposits of the McPherson formation to the southeast, it seems evident that the terrace deposits are a western equivalent of the beds at the McPherson type locality.

PALEONTOLOGY

The study of the paleontology of this region can be considered only preliminary. During the course of mapping the terraces numerous exposures were explored for the presence of fossils, and, time being limited, a few of the most promising exposures were selected for further study. Numerous molluscan remains were found to have been exposed by weathering at each of these localities. Subsequent collecting resulted in the recovery of scanty and fragmentary vertebrate remains.

INVERTEBRATE FOSSILS

Fossil mollusks are not uncommon at many places along the terraces discussed here, but only three localities have been studied in sufficient detail to justify listing of the forms identified. The work on these localities cannot be considered complete, but, inasmuch as the methods of collecting that were employed resulted in the recovery of such small forms as *Carychium*, it is likely that the reported local assemblages of fossils, here termed "faunules," include the majority of all species in the respective deposits.

TOBIN FAUNULE

Deposits in Sec. 35, T. 14 S., R. 11 W., Russell County, yielded fossils that collectively are termed the "Tobin faunule," the name being derived from the property owner. The matrix in which the fossils are embedded consists of flood-plain silt, almost completely devoid of sand and lacking pebbles. The color of the beds ranges from light buff to greenish gray, the greenish hue being most evident when the silt is wet. Volcanic ash and higher deposits that are recorded in a measured section previously given overlie the beds under consideration, but no fossils have been recovered from the ash or succeeding beds.

The following list of forms that have been identified in the Tobin faunule contains eleven species of aquatic mollusks and fourteen terrestrial gastropods.

THE TOBIN FAUNULE, FROM SEC. 35 T. 14 S., R. 11 W., RUSSELL COUNTY KANSAS

Pelecypod
- *Pisidium compressum* Prime

Aquatic gastropods
- *Aplexa hypnorum* (Linnaeus)
- *Ferrissia parallela* (Haldeman)
- *Gyraulus parvus* (Say)
- *Lymnea dalli* Baker
- *Lymnea obrussa* (Say)
- *Lymnea palustris* (Müller)
- *Physa anatina* Lea
- *Pomatiopsis cincinnatiensis* (Lea)
- *Pomatiopsis lapidaria* (Say)
- *Valvata tricarinata* (Say)

[14] John C. Frye and Claude W. Hibbard, "Stratigraphy and Paleontology of a New Middle and Upper Pliocene Formation of South Central Kansas," *Jour. Geol.*, Vol. XLIX (1941), pp. 261–78; Lohman and Frye, *op. cit.*

Terrestrial gastropods
Carychium exiguum (Say)
Cochlicopa lubrica (Müller)
Discus cronkhitei anthonyi (Pilsbry)
Euconulus chersinus (Say)
Gastrocopta armifera (Say)
Hawaiia miniscula (Binney)
Helicodiscus parallelus (Say)
Hendersonia occulta (Say)
Pupilla muscorum (Linnaeus)
Stenotrema monodon (Rackett)
Succinea grosvenori Lea
Vallonia costata (Müller)
Vertigo modesta (Say)
Zonitoides arboreus (Say)
Fossilized eggs of some terrestrial gastropod

WILSON VALLEY FAUNULE

This assemblage of mollusks was collected from fine gray silt beneath volcanic ash in Sec. 38, T. 13 S., R. 10 W., Lincoln County. The fossil-bearing beds here are more sandy than deposits at the Tobin locality, and there is even an occasional pebble, but, on the whole, they have the characteristics of flood-plain silts. The faunule is named from its location in the high-level valley near Wilson, Kansas, that has been designated as the "Wilson Valley." The relations of the fossiliferous zone to other strata are indicated in a measured section given above.

A total of twenty-nine species of mollusks—nineteen terrestrial and ten aquatic—comprise the Wilson Valley faunule as now known.

THE WILSON VALLEY FAUNULE, FROM SEC. 38, T. 13 S., R. 10 W., LINCOLN COUNTY, KANSAS

Pelecypods
Pisidium compressum Prime
Pisidium sp.
Sphaerium sp.
Aquatic gastropods
Amnicola limosa parva (Say)
Helisoma trivolvis (Say)
Gyraulus parvus (Say)
Lymnea (*Acella*) *haldemani* (Binney)
Lymnea parva Lea
Valvata lewisii Currier
Valvata tricarinata (Say)
Terrestrial gastropods
Carychium exiguum (Say)
Carychium exile H. C. Lea
Cochlicopa lubrica (Müller)
Discus cronkhitei anthonyi (Pilsbry)
Hawaiia miniscula (Binney)
Helicodiscus parallelus (Say)
Gastrocopta armifera (Say)
Gastrocopta contracta (Say)
Gastrocopta procera (Gould)
Gastrocopta tapanniana (Adams)
Pupilla hebes (Ancey)
Stenotrema monodon? (Rackett)
Strobilops affinis Pilsbry
Succinea grosvenori Lea
Vallonia costata (Müller)
Vallonia pulchella (Müller)
Vertigo gouldi (Binney)
Vertigo milium (Gould)
Zonitoides arboreus (Say)
Snail eggs, species unknown

REZABEK FAUNULE

The most interesting, in many respects, of the faunules studied was obtained from deposits in Sec. 20, T. 13 S., R. 11 W., Lincoln County. This assemblage is called the "Rezabek faunule," from the name of the property owner. The sediments bearing the fossils are composed of fine gray silts containing considerable fine to coarse sand. Gravel and sand underlie the fossiliferous silts, and the shell-bearing zone is exposed around the margins of a gravel pit. No volcanic ash appears in the section exposed by excavations in the gravel pit.

Of the twenty-eight species of mollusks represented in the Rezabek faunule, sixteen are aquatic in habit and the remaining twelve are terrestrial.

THE REZABEK FAUNULE, FROM SEC. 20, T. 13 S., R. 11 W., LINCOLN COUNTY, KANSAS

Pelecypods
Pisidium compressum Prime
Pisidium sp.
Sphaerium sp.

Aquatic gastropods
Amnicola limosa (Say)
Gyraulus cf. *hirsutus* (Gould)
Gyraulus parvus (Say)
Ferrissia parallela (Haldeman)
Helisoma trivolvis (Say)
Lymnea galbana (Say)
Lymnea humilis modicella (Say)
Lymnea palustris Müller
Lymnea sp.
Menetus kansasensis Baker
Physa anatina Lea
Planorbula armigera (Say)
Valvata tricarinata (Say)

Terrestrial gastropods
Gastrocopta contracta (Say)
Gastrocopta procera (Gould)
Gastrocopta procera cf. *mcclungi* Hanna and Johnson
Gastrocopta tapanniana (C. B. Adams)
Hawaiia miniscula (Binney)
Helicodiscus parallelus (Say)
Succinea cf. *retusa* Lea
Stenotrema sp. (immatures)
Strobilops affinis Pilsbry
Vallonia costata (Müller)
Vallonia cf. *pulchella* (Müller)
Vertigo gouldi (Binney)
Vertigo hibbardi Baker

All specimens represented in the Rezabek and preceding lists are catalogued in the collections of the University of Kansas.

DISCUSSION OF THE FAUNULES

Faunal lists are frequently misleading, but in the case of the Tobin faunule the greater number of terrestrial gastropod species seems to reflect actual ecological conditions, since the forms represented by the greatest numbers of individuals are in approximate order: *Vallonia costata*, *Helicodiscus parallelus*, *Discus cronkhitei anthonyi*, *Pupilla muscorum*, *Gastrocopta armifera*, and *Hendersonia occulta*. Several of the aquatic species are represented in our collections by single individuals.

Most of the terrestrial species indicate a wooded terrain, and most of them require a more humid climate than obtains today in the region where they were found. It has been shown by Henry van der Schalie[15] that *Hendersonia* not only lives in woodlands, but almost invariably is restricted to areas near streams, even where they may be subject to overflow of the stream.

Ferrissia, *Gyraulus*, and *Valvata* are snails that live in pools and streams. *Aplexa*, the *Lymneas*, and *Physa* inhabit more or less temporary pools. *Pomatiopsis*, *Succinea*, and *Lymnea dalli* are snails that frequent mud flats, marshy edges of pools and other moist places. Thus the molluscan assemblage indicates a wooded region near a stream, probably a flood plain that contained local stagnant pools and marshes.

Although a majority of species in the Wilson Valley faunule is terrestrial, study of the relative number of individuals belonging to the various species suggest an aquatic environment at this locality. *Gyraulus*, *Valvata*, *Helisoma*, and *Pisidium* are the predominant forms, whereas many of the terrestrial forms are represented in our collections by single individuals or at most by a few specimens. Nevertheless, such gastropods as *Helicodiscus*, *Strobilops*, *Discus*, *Stenotrema*, and *Cochlicopa* indicate the presence of near-by woodlands, and *Lymnea parva*, *Carychium*, and *Succinea* are prevalent forms in moist situations, though not actually occurring in the water. *Pisidium compressum*, *Lymnea* (*Acella*) *haldemani*, and *Amnicola limosa parva* have been reported largely from the rather deep water of larger streams and lakes. Attempts to reconstruct the conditions prevailing in the Wilson Valley, as judged

[15] "*Hendersonia occulta* (Say) in Michigan: Its Distribution, Ecology, and Geological Significance," *Mus. of Zoöl., Univ. of Mich., Occasional Paper No. 399* (1939).

from the nature of the observed molluscan fossils, should incorporate the characters of environment belonging typically to a permanent stream of fairly deep and perhaps quiet water, bordered by moist flats and near-by timbered slopes.

In spite of the fact that several species found in the Tobin faunule were not found at the Wilson Valley locality and that the reverse is equally true, it seems evident that these two assemblages of mollusks possess close affinity, the differences being largely ecological. The nature of the sediments, the relation of the fossil-bearing beds to the ash deposit, and the similarities in the vertebrate remains collected from the two localities are further indications of equivalence in age. The deposits were formed before the early Pleistocene Saline River abandoned the Wilson Valley. It seems reasonable to conclude that the faunules were living at a time when the early Pleistocene Saline was losing competency, perhaps owing to overload from glacial outwash or from reduced velocity or volume of water. The Tobin faunule seemingly existed farther from the main stream than the Wilson Valley faunule. This is shown by the predominance of terrestrial species in the former and of aquatic forms in the latter.

The Rezabek faunule does not seem to be closely related to the others discussed. The deposit containing the Rezabek mollusks is thought to have been formed under turbulent stream conditions, for broken shells are present in impressive numbers, making collection of good specimens both difficult and tedious. The predominance of such forms as *Menetus, Gyraulus, Valvata, Helisoma, Planorbula, Pisidium, Sphaerium,* and the large *Lymneas,* together with the fact that fish remains are common, indicates a stream or lake environment. Terrestrial gastropods that frequent wooded areas are present in the faunule in considerable numbers as species, but they are very poorly represented as individuals. This indicates that the land snails were carried in from the surrounding slopes.

Although studies in the Russell-Ellsworth area have not progressed sufficiently to allow many definite conclusions, the presence of *Menetus kansasensis* and *Vertigo hibbardi*,[16] and the fact that many shells tend to vary considerably from typical form, may indicate a greater age for beds at the Rezabek locality than for those at the Tobin and Wilson Valley localities. The two species just mentioned have been reported only from the Rexroad member[17] (upper Pliocene) of the Ogallala formation, but, inasmuch as their vertical range is not known, undue significance should not be attached to their presence in the Rezabek faunule.

It is not now possible to assign a definite age within the Pleistocene to the deposits under consideration. So little is yet known of the Pleistocene invertebrates of this region that there is no certainty as to whether the faunules represent an initial or a closing phase of an interglacial stage. As a working hypothesis, it seems reasonable to assume that the Rezabek faunule represents deposits produced during an active, competent stage of the early Pleistocene Saline River flowing through the Wilson channel and that the Tobin and Wilson Valley faunules lived during a declining stage of this stream. Intensive study of

[16] F. C. Baker, "New Land and Freshwater Mollusca from the Upper Pliocene of Kansas and a New Species of *Gyraulus* from Early Pleistocene Strata," *The Nautilus*, Vol. LI (1938), pp. 126–31.

[17] Frye and Hibbard, "Pliocene and Pleistocene Stratigraphy and Paleontology of the Meade Basin, Southwestern Kansas," *Kan. Geol. Surv. Bull. 38*, Part XIII (1941), pp. 407–10.

the Pleistocene deposits in the Smoky Hill River Valley will be necessary in order to establish the exact relation of the three groups of mollusks to the complete Pleistocene history of the Smoky Hill River Valley.

Vertebrate Fossils

The occurrence of fossil vertebrates in terrace deposits of Russell, Ellsworth, and Lincoln counties is well known to the inhabitants of this region. Elephant teeth, because of their large size, have attracted the special attention of workmen and, along with some other bones, have been kept by local residents for years. Exact data concerning many of these fossils have been lost, although it is known that they were taken from gravel or sand pits of the region. As a rule, these pits are poor places to collect fossils. Most of the exposures in them are barren, although a few yielded scattered fragmentary remains. Except for two elephant teeth, which were donated to the museum, all the vertebrate fossils listed below were found either in association with the invertebrates that have been reported or at other exposures along streams and road cuts of the area.

Fishes, Amphibians, Reptiles, and Birds

Fish remains were found at the locality of the Wilson Valley faunule, and an abundance of fragmentary bones, especially gar vertebrae and scales, were obtained at the Rezabek locality.

Frog, or toad, and salamander vertebrae were collected with the Rezabek and Tobin invertebrate faunules.

Lizard or snake caudal vertebrae and remains of turtles were found in association with the Wilson Valley and Rezabek faunules.

A bird bone was found at the Rezabek locality.

Mammals

Sorex sp.—A right lower ramus (No. 6183) bearing M_1–M_3 was collected at the Wilson Valley locality in Lincoln County. It is different from the other fossil species of *Sorex* found in Kansas.

Cynomys ludovicianus (Ord.).—A number of lower jaws and fragmentary skulls of this species of prairie dog, as well as other parts of the skeleton, have been found in flood-plain sediments of the intermediate terrace in Sec. 27, T. 14 S., R. 11 W., Russell County (Fig. 3). The fossils were 29 feet below the surface, buried in old burrows in the silt. Inasmuch as the exposure did not show a vertical section of a burrow, it is not known at what level the exits were placed. There is no evidence of an old prairie-dog town on the surface, but the remains are certainly somewhat younger than the deposit that contains the burrows. Five burrows were located in the nearly vertical bank (Fig. 3), all at the same level, and fossil prairie dogs were found in each of them. It is hoped that future work will show the age of this dog town in relation to that of the deposit.

Geomys sp.—Two molar teeth were found in association with the Wilson Valley invertebrates.

Castor sp.—The molar tooth of this genus of beavers was obtained from a gravel pit in the northwest quarter of Sec. 11, T. 15 S., R. 9 W., in Ellsworth County.

Castoroides sp.—Part of an upper incisor of an extinct type of beaver was found associated with the Rezabek faunule.

Mastodon sp.—Part of a tooth was collected from the gravel pit that yielded the tooth of *Castor*. It belongs to a species of mastodon that is older than *M. americanus* Kerr.

Ondatra sp.—An upper molar was

found with the Rezabek faunule in Lincoln County.

Microtus sp.—A right lower ramus (No. 6304) bearing M_1–M_2 was taken at the Tobin locality in Russell County. Vertebrate remains are rare in this deposit. A left lower ramus bearing M_1–M_2, the same form as the above, was found associated with the Wilson Valley invertebrates. A lower jaw bearing M_1 and M_2, from the Rezabek locality, belongs to the subgenus *Pedomys*, thus differing from the *Microtus* remains found in the other two deposits.

Archidiskodon imperator (Leidy).—Rubey and Bass[18] reported a tooth which they collected and sent to the United States National Museum for identification. The tooth was taken from the southeast quarter of Sec. 25, T. 14 S., R. 14 W., on the west side of Fossil Creek, Russell County. Whether it came from deposits of the high terrace or from an intermediate one is not known. It may have been redeposited. The tooth is now in the Kansas University Museum of Vertebrate Paleontology (No. 2915). A detailed description of this specimen is given by Hay.[19] Specimen No. 3681, collected by W. H. Biays, from the Henry Reinhardt gravel pit in the northeast quarter of Sec. 36, T. 14 S., R. 15 W., in Russell County, and specimens Nos. 3709 and 6177, mentioned below, were identified by Erwin H. Colbert. Biays' specimen, a large molar, may have come from the high terrace. It seems to have been reworked, however, inasmuch as it was free from the skull and no other bones of the skeleton were found associated with it. Specimen No. 3709, a molar tooth collected by Gordon Cunningham from the Schwartz gravel pit south of Wilson, in the SW¼, Sec. 30, T. 14 S., R. 10 W., Ellsworth County, came from the intermediate terrace. The tooth shows signs of abrasion and may have been redeposited from the high terrace. Specimen No. 6177, part of two molars, was taken from a badly shattered skull with associated bones, from a plowed field in Sec. 28, T. 13 S., R. 10 W., Lincoln County. The skeleton was in place in flood-plain deposits at the high-terrace level in the Wilson Valley.

Equus cf. *niobrarensis* Hay.—Two fragmentary molars were found that seem referable to this form. One was from the Rezabek locality and the other from a gravel pit in the NW¼, Sec. 11, T. 15 S., R. 9 W., Ellsworth County.

Camelops sp.—One large incisor was found in the above gravel pit in Ellsworth County in association with teeth of horse, mastodon, and *Castor*.

Symbos cf. *cavifrons* (Leidy).—Cope, in 1877, secured from Jacob Fowler of Wilson, Kansas, part of a skull of a muskox. The skull, now in the American Museum of Natural Nistory (No. 12699), came from near Wilson. It has not been possible to find accurate information concerning the exact locality where this specimen was collected. Barnum Brown[20] considered that the skull belongs to *Symbos*, and Hay[21] likewise referred it to *Symbos*, probably *S. cavifrons*, but J. A. Allen[22] assigned it to *Ovibos*. The skull is

[18] *Op. cit.*, p. 21.

[19] O. P. Hay, "The Pleistocene of the Middle Region of North America and Its Vertebrated Animals," *Carnegie Inst. Wash. Pub. No. 322a* (1924), p. 95.

[20] "The Conard Fissure, a Pleistocene Bone Deposit in Northern Arkansas: With Descriptions of Two New Genera and Twenty New Species of Mammals," *Memoirs Amer. Mus. Nat. Hist.*, Vol. IX, Part IV (1908), p. 202.

[21] *Op. cit.*, p. 181.

[22] "Ontogenetic and Other Variations in Muskoxen, with a Systematic Review of the Muskox Group, Recent and Extinct," *Memoirs Amer. Mus. Nat. Hist.*, Vol. I, Part IV (new ser., 1913), pp. 203–14.

badly abraded and has lost many of the characters necessary for accurate identification.

CORRELATION

Study of the fossil vertebrates from the Russell-Ellsworth area does not yet provide sufficient basis for correlation with other known Pleistocene faunas of Kansas. Two distinct horizons have yielded vertebrate fossils. The high-terrace deposits, which yielded the Tobin and Wilson Valley faunules, are considered to be equivalent in age, as indicated by physiographic evidence, similarity of the snails, and the *Microtus* teeth. As yet the Bezabek faunule has yielded none of the vertebrates that have been taken from the Tobin and Wilson Valley localities. The fossil-bearing sediments at the latter places are flood-plain deposits (silts), which underlie a bed of volcanic ash, and it may be noted that the vertebrates collected from them to date are entirely different from those obtained from a similar Pleistocene flood-plain deposit, which underlies an ash bed in Meade County, southwestern Kansas.

The intermediate terrace has not yielded any fossils that may be considered endemic to the deposit. The elephant teeth show signs of abrasion and may have been redeposited from the high-terrace sediments. The lack of knowledge concerning the vertical range of vertebrate forms is a great handicap in correlating beds within the Kansas Pleistocene, even when the question of redeposition does not intrude itself. Therefore, much more complete information is necessary before correlation of separated Pleistocene deposits in Kansas is attempted.

PLEISTOCENE DRAINAGE CHANGES

The terraces of Smoky Hill Valley assume considerable significance when they are considered from a regional standpoint. They substantiate earlier conclusions that the McPherson formation (restricted) was deposited by a stream flowing southward from the present valley of the Smoky Hill to the Arkansas Valley, and they indicate that the headwaters portion of the Saline River entered the early Pleistocene Smoky Hill River well upstream from the junction of that stream with the McPherson channel. The observations that are reported here strengthen the hypothesis that during early Pleistocene time there was no through drainage eastward across the Flint Hills and that the master-stream of this part of Kansas flowed southward, following the Smoky Hill Valley (reversed) from Salina to west of Lindsborg, the McPherson channel south to the Arkansas, and the Arkansas Valley south to the Oklahoma state line. These terraces, in addition, constitute an early Pleistocene datum extending over much of northern and central Kansas, which, it seems probable, can be traced northward to the Nebraska line and so effect a more definite correlation with the various Pleistocene formations that have been described in that state.[23]

The disruption of this early Pleistocene drainage pattern occurred during mid-Pleistocene time, when the major south-flowing stream abandoned the McPherson channel. Concomitantly with the abandonment of the McPherson channel, the waters of this area escaped eastward through the Flint Hills, resulting in the lowering of the level of the bed of the Smoky Hill River. The intermediate terraces (below the level of the floor of Wilson Valley) along both the Saline

[23] A. L. Lugn, "Nebraska in Relation to the Problems of Pleistocene Stratigraphy," *Amer. Jour. Sci.*, Vol. CCXXXVII (1939), pp. 851–84; "The Pleistocene Geology of Nebraska," *Neb. Geol. Surv. Bull. 10* (1935), pp. 1–213.

and the Smoky Hill valleys are Pleistocene in age, and so it seems certain that this major shift in drainage occurred after the abandonment of the McPherson channel and before the close of the Pleistocene.

Although the cause for this major shift in the drainage of central and northern Kansas at about the mid-Pleistocene has not been determined with certainty, it seems probable that it was brought about by a series of piracies. The Kansas River apparently was established as an east-flowing stream across the Flint Hills area after the close of the Kansan; this course to the east afforded a lower outlet than the outwash-choked McPherson channel, and the earlier stream was captured and reversed as far west as Marquette. Some time later a stream working headward, west from Salina, captured the early Pleistocene Saline at the north end of Wilson Valley. It will be possible to date this capture closely only after detailed study has been made of the intermediate terraces that developed along the Saline Valley after the capture had been completed.

Many of the details in the drainage history of central and northern Kansas are lacking and can be filled in only after additional studies have been made of the valleys of the Saline, Kansas, Solomon, Smoky Hill, Republican, and Arkansas rivers.

ACKNOWLEDGMENTS.—Acknowledgment is made to Thomas G. Payne, of the University of Kansas, for advice and aid in the preparation of the section on the lithology of the terrace deposits; to Calvin Goodrich, of the University of Michigan, for aid in the determination of mollusks; and to R. C. Moore for aid in the preparation of the manuscript.

BEDDING-SLIP MOVEMENTS IN FAULT BLOCKS SOUTHWEST OF THE LOS PINOS MOUNTAINS, NEW MEXICO

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ABSTRACT

Brecciated zones occur along bedding planes in certain Pennsylvanian limestone cuestas which dip gently southwest off pre-Cambrian formations of the Los Pinos uplift in central New Mexico. The zones are thoroughly silicified and are confined to triangular blocks which are bound on two sides by normal faults of Basin and Range type. Breccias of the bedded zones capping the cuestas are continuous with similar silicified zones along the steeply dipping normal faults. The outcrops of these bedded breccias proved useful in locating the less evident breccias of the normal faults. The fault blocks are domed, and slickensides suggest that the brecciated zones along the bedding were formed by movements of beds upward toward the crest of anticlines during initial folding and by subsequent slipping of beds down dip. Silicification of the breccias was probably accomplished during the Tertiary.

INTRODUCTION AND GENERAL RELATIONS

Interesting bedding-slip movements in Pennsylvanian limestone cuestas, southwest of the Los Pinos Mountains in central New Mexico, were studied in connection with the detailed mapping of the mountain range in the summer of 1941 by a field party from Northwestern University.[1] Brecciated zones resulting from bedding slips connect with less well-exposed breccias that mark the outcrops of steeply dipping normal faults. Thorough silicification of the bedded breccias enables them to form resistant outcrops on the crests and dip slopes of the cuestas, and such outcrops were found to be useful in locating the breccias of the steeply dipping normal faults.

The Los Pinos Range is composed of a thick series of pre-Cambrian rhyolite flows and sediments intruded by granite. Pennsylvanian limestones, sandstones, and shales rest on the extremely irregular pre-Cambrian surface and in the southern third of the range form a series of cuestas dipping from 3° to 5° southeast, south, and southwest off the core of the uplift. A major thrust, probably of Laramide orogeny, extends along the entire length of the eastern side of the range and brings pre-Cambrian formations against and over the Paleozoic sediments to the east. The strike of the thrust averages N. 20° E., and the dip is about 45° toward the west. A throw of approximately 700 feet in the northern part of the range decreases southward, where the fault departs from the pre-Cambrian rocks and traverses the Pennsylvanian and Permian formations.

The faults discussed in this paper lie southwest of the Los Pinos Mountains proper (Fig. 1). They are assumed to be Tertiary in age, since block faults of Basin and Range type characterize the district. The normal faulting here is in in-

[1] J. T. Stark and E. C. Dapples, "Structure of the Los Pinos Mountains" (abstr.), *Bull. Geol. Soc. Amer.*, Vol. LII (1941), p. 1936.

teresting contrast to the earlier thrusting of the Los Pinos Mountains which is more characteristic of the Laramide thrusting in the southern Rocky Mountains.

sediments, which average from 3° to 5° away from the mountains. In each of these exceptions a tilted triangular block has been formed by steeply dipping normal faults. Doming of the blocks pre-

FIG. 1.—Index map showing location of the faulted cuestas with reference to the Los Pinos Range

BLOCK-FAULTED CUESTAS

Among the numerous cuesta hills dipping southward from the Los Pinos Mountains there are two—hereafter designated as "East" and "West Cuestas"—showing striking departures from the general regional dips of the Paleozoic

ceded or accompanied the faulting. Minor folds, especially prominent on the West Cuesta, complicate the structures.

EAST CUESTA

The more eastern of the two cuestas lies in Section 5, T. 1 N., R. 3 E., New

Mexico Principal Meridian.[2] The fault block forms a wedge-shaped area of approximately a third of a square mile, with the apex of the wedge pointing north-northeast. Steeply dipping normal faults bound the block on the east and northwest. The beds in the fault block are folded into an anticline plunging to the west.

The cuesta proper is confined to the southern limb of the anticline. The hill rises 500 feet above the arroyo-channeled lowlands, which have been cut below the extensive plainlike pediment on the west side of the Los Pinos Range. The cuesta is supported by massive Pennsylvanian limestones which average in strike between N. 30° and 60° W., and in dip between 8° and 13° southwest.

The crest of the cuesta is capped by 20 feet of silicified limestone breccia (Fig. 2). Erosion remnants of the breccia extend down the dip slope to the southwestern base of the hill where the breccia disappears beneath Permian red beds. Thus the breccia forms a zone approximately 20 feet thick between recognizable Pennsylvanian and Permian beds and represents a silicified limestone bed at the top of the Pennsylvanian section. An unconformity is reported between the two systems[3] in this region, but no definite evidence for such a relationship was found by members of the Northwestern party working on the Paleozoic stratigraphy.[4] Silicified breccia, continuous with and similar to the bedded breccia capping the cuesta, cuts steeply across the bedding on both sides of the wedge-shaped apex of the block formed by the bounding normal faults.

The fault on the east side of the block strikes N. 7° E., and dips from 80° to 85° westward (Fig. 3). The upthrow side is on the east. Thin shaly Pennsylvanian limestone beds on the east side are brought against massive beds which are 200 feet higher stratigraphically in the Pennsylvanian section. The shaly limestones on the upthrow side have been dragged from their southerly regional dip of about 4° to a dip of 80° where they plunge into the fault plane. Although the breccia is only spottily preserved along the fault, a thoroughly silicified zone of breccia, about 15 feet thick, extends from the arroyo at the northeast base of the cuesta scarp to the silicified breccia capping the crest.

FIG. 2.—View of East Cuesta from the west, showing silicified breccia forming the dip slope.

The fault on the northwest side of the block ranges in strike from N. 35° to 40° E. and has an average angle of dip of 65° westward. The downthrow side is on the west. The throw is sufficient to cut out a large part of the Paleozoic section, although the amount was not determined.

The East Cuesta block is domed along an anticlinal axis striking east and plunging westward at angles that increase from

[2] Cibola National Forest map.

[3] W. T. Lee and G. H. Girty, "The Manzano Group of the Rio Grande Valley, New Mexico," *U.S. Geol. Surv. Bull. 389* (1909), p. 20.

[4] E. C. Dapples, H. E. Garrison, and R. H. Wilpolt, communication in the field.

nearly horizontal at the crest of the hill to 20° on the west slope. The fold is asymmetric. The beds of the south limb dip from 8° to 13° northwest and those of the north limb dip as much as 45° northwest. The axial plane is, therefore, inclined with a southeast dip.

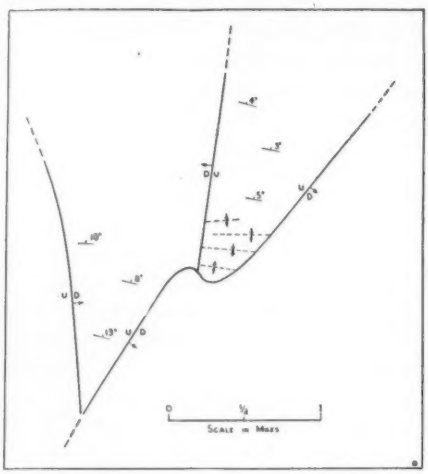

FIG. 3.—Sketch showing plan view of the faulted cuestas.

WEST CUESTA

One mile southwest of the East Cuesta is a larger fault block, roughly triangular in plan, with its apex pointing north-northeast. The part of the block forming the present hill approximates a square mile, although the tilting has doubtless affected a much larger area to the south.

The apex of the wedge-shaped fault block forms the crest of the cuesta, and a broad dip slope extends to the southwest. Massive beds of Pennsylvanian limestone make up the hill. Folding has modified the simple cuesta structure by doming the beds of the dip slope and crumpling them into several small anticlines and synclines. The average strike of the beds is N. 60° W.; the general dip about 4° to the southwest. Small-scale crumpling of the beds has caused the dip to vary in amount and direction, but it is rarely more than 10°. The contortion is more intense in the narrow northeast part of the fault block than across the broad dip slope.

The steep east and west scarps of the West Cuesta are parallel to normal faults which strike, respectively, N. 8° E. and N. 35° E., with dips approaching 60° eastward on the east side, and 60° westward on the west side of the cuesta. The lowlands east and west of the hill are underlain by Permian red beds. The structure of the block is accordingly a wedge-shaped horst of Pennsylvanian limestone between downdropped Permian sediments.

The fault along the east side of the West Cuesta ends abruptly against the fault which bounds the western side of the block. This western fault bends around the narrow northeast end of the hill and passes northeast to become the fault which forms the western boundary of the East Cuesta (Fig. 3). It seems entirely possible that this fault may continue in a northeasterly direction to form the border fault of the Los Pinos Range. No concrete evidence was found, however, supporting the presence of such a border fault; if one exists, it is apparently completely buried beneath the pediment that extends to the abruptly rising western flanks of the mountains.

Silicified breccias from 15 to 20 feet thick occur in the steeply dipping normal fault zones (Fig. 4). Similar breccia lies along the crest of the cuesta parallel to the bedding and is preserved in remnants across the long dip slope. The parallelism is repeatedly shown in isolated outcrops of the breccia on the limestone where the contacts can be followed continuously around the outcrop. As in the East Cuesta, the bedding breccia contin-

ues up to the sides of the upfaulted block and then bends over the edge in continuous outcrop with the steeply dipping silicified breccia of the normal faults. This relationship is strikingly exposed along the east and northwest sides of the cuesta near the apex of the block.

FIG. 4.—View of West Cuesta from the east, showing the silicified breccia parallel to the bedding on the dip slope and continuous with the steeply dipping, silicified breccia of the normal fault forming the eastern escarpment.

BEDDING-SLIP MOVEMENTS

Brecciation and subsequent silicification of fractured zones have favored definite horizons parallel to the bedding of the Pennsylvanian limestone. Initial fracturing of such beds is believed to be due to small bedding-slip movements during folding and to reverse movements along the same zones caused by block faulting. Reasons for this interpretation are given below.

The cuesta blocks are thought to have been domed either before or contemporaneously with the normal faulting; if earlier faulting had occurred, compressive forces would be expected to find release along such breaks rather than cause complex doming across the relatively narrow apexes of the triangular fault blocks. Slipping of beds toward crests of folds resulted in some beds being thoroughly fractured. Evidence for such upward movements is found in many slickensided surfaces on bedding planes, which indicate clearly that updip slipping of overlying beds took place. With one exception, the displacement of individual beds was slight, since the compression fractures formed within a specific bed are nearly vertical.

The exceptional movement, namely, the one of greatest magnitude, occurred along the now brecciated and silicified zone parallel to the bedding. In the East Cuesta this zone, about 20 feet thick, is at the top of the Pennsylvanian limestone and directly below overlying Permian red beds. If the Pennsylvanian had been exposed to active weathering processes for any length of time before the deposition of the Permian strata, a zone of weakness may have developed, but evidence for such a period of weathering is lacking. The difference in character between Pennsylvanian and Permian strata appears to provide a zone favorable for the development of fractures. That movements were more intense in the silicified breccia than elsewhere is suggested by the much greater prominence of slickensides in this zone. During or after tilting of the blocks by faulting and folding, a reverse movement took place and numerous slickensides were again developed in the more highly brecciated zone, indicating slipping of overlying beds downdip in a direction opposite to that of the earlier movement upward toward the crests of anticlines. These slickensided surfaces are not to be confused with the abundant small slickensides which occur in fault breccias and shear zones, commonly showing on several sides of blocks from a few inches to a few feet in diameter. Such characteristic surfaces are present on blocks of the silicified breccia, but the diagnostic slickensides of bedding movements are on a much larger scale and leave little doubt

that two dominant directions of bedding slip in opposite directions occurred. Some slipping movements downdip in the brecciated zone continued well after silicification had started, and a distinction is made between slickensides which were developed on limestone and slickensides which were clearly formed after the brecciated zone was thoroughly silicified. Graphic evidence of the two directions of movement is found in the northwest part of the East Cuesta where slickensides of the last movement have been superimposed on slickensides of the earlier updip slipping.

The stratigraphic position of the brecciated zone is definitely located in the East Cuesta by the overlying Permian beds. The position of the breccia in the dip slope of the West Cuesta has not been established beyond the fact that it overlies Pennsylvanian limestone that resembles the limestone beds of the East Cuesta below the breccia. In the cross section (Fig. 5) between the two hills a throw is assumed for the central fault (*A*) which would place the dip-slope breccias of each cuesta at the same stratigraphic horizon. In thickness and petrographic character the two breccias appear identical.

Movements parallel to beds resulting from adjustments near faults have been described in connection with both normal and reverse faulting.[5] In his proposed classification of bedding-plane movements, Behre[6] includes these faults under the "transecting accessory type." In the majority of cases described, bedding-slip movements have been associated with thrusting, but included in this type are also bedding slips associated with normal faults such as Emmons and Calkins described in the Phillipsburg quadrangle, Montana,[7] and to which the bedding-slip movements in the Los Pinos area appear somewhat analogous. The brecciation along bedding in the present area is believed to have been initiated during folding and later accentuated by downdip movements associated with normal faulting and would thus be classified as the "transecting accessory type."

Silicification of the limestone is directly related to the intensity of the fracturing. It is most thoroughly developed in the central parts of the fault zones where the breccia blocks are quartzite-like in appearance and show none of the original carbonate. Thin sections from specimens across the zones show a gradual transition from the completely silicified rock into the unaltered limestones. This transition zone ranges in width from 2 to 4 feet and is cut in many places by silicified stringers along joints and fractures.

SIMILAR STRUCTURES IN THE JOYITA HILLS

An opportunity to use outcrops of silicified breccias on dip slopes of cuestas as guides to the location of steeply dipping normal faults was furnished during reconnaissance in the Joyita Hills, a small mass of pre-Cambrian granite about $2\frac{1}{2}$ miles west of the Los Pinos Mountains. Dipping westward from and lying around the granite mass are Pennsylvanian and Permian sediments and Tertiary lava flows. Darton and Denny have briefly

[5] S. F. Emmons, J. D. Irving, G. F. Loughlin, "Geology and Ore Deposits of the Leadville Mining District, Colorado," *U.S. Geol. Surv. Prof. Paper 148* (1927), pp. 64–65; D. F. Hewett, "Geology and Ore Deposits of the Goodsprings Quadrangle, Nevada," *U.S. Geol. Surv. Prof. Paper 162* (1931), pp. 52–53; W. H. Emmons and F. C. Calkins, "Geology and Ore Deposits of the Phillipsburg Quadrangle, Montana," *U.S. Geol. Surv. Prof. Paper 78* (1913), pp. 183–84; C. H. Behre, Jr., "Bedding-Plane Faults and Their Economic Importance," *A.I.M.E. Tech. Pub. 767* (1937), pp. 9–13.

[6] *Op. cit.*, pp. 9–13.

[7] *Op. cit.*, pp. 183–84.

described the area and have given generalized structure sections.[8]

Bedding-slip movements have occurred here on a much larger scale than in the area southwest of the Los Pinos Range, judging by the abundance and greater mineralization of the resulting breccias and associated shearing zones in west of the Los Pinos Range. Time permitted the testing of only two of the breccia-capped cuestas, but on each a breccia was found that was continuous with silicified breccia along steeply dipping normal faults.

Detailed study of the Joyita Hills is planned for the near future.

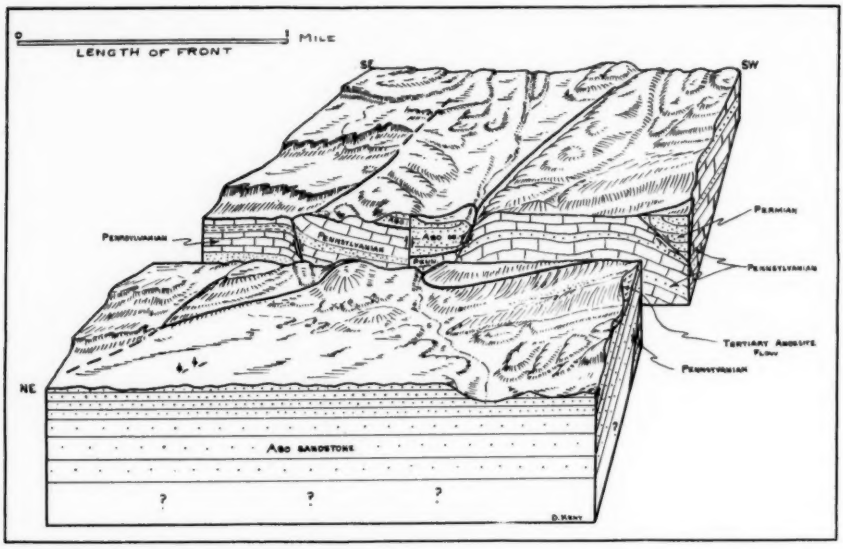

FIG. 5.—Block diagram and cross sections across the faulted cuestas

the granite. The unconformity between the pre-Cambrian and the overlying Pennsylvanian limestone is marked by such a breccia. Remnants of bedded silicified breccias crop out in several dip slopes of the Carboniferous cuestas north and west of the granite mass. The question was raised as to whether or not these outcrops might be followed up dip slopes and be continuous with breccia along normal faults, as in the area south-

[8] N. H. Darton, "Red Beds and Associated Formations in New Mexico," *U.S. Geol. Surv. Bull. 794* (1928), pp. 84–85; C. S. Denny, "Tertiary Geology of the San Acacia Area, New Mexico," *Jour. Geol.*, Vol. XLVIII (1940), pp. 82, 101, 104.

SEQUENCE OF EVENTS

1. Carboniferous sediments which now form cuestas on the southerly slopes of the Los Pinos Mountains were deposited on the extremely irregular surface of the pre-Cambrian core of the range.

2. Thrusting in post-Permian time, probably Laramide, brought the buried pre-Cambrian against and over the Paleozoic sediments along the east side of the range. The original southerly dips of the sediments on the south slopes of the range may have been increased at this time.

3. Erosion carved the sediments into

a series of cuestas dipping gently off the Los Pinos uplift.

4. Steeply dipping normal faults resulting in tilted blocks of Basin and Range type occurred, probably in Tertiary time. Preceding or contemporaneous with the faulting, the blocks were domed and small folds were formed across the cuestas. Brecciated zones were developed along the normal faults and also in zones parallel to the beds, first by movements updip toward the crests of the folds and subsequently downdip in the opposite direction.

5. The brecciated zones were well silicified by silica-bearing waters. These in all likelihood were warm solutions originating from the same sources responsible for the Tertiary lava flows which are present in near-by outcrops south and west of the faulted cuestas.

ACKNOWLEDGMENTS.—The authors are indebted to E. C. Dapples, H. E. Garrison, and R. H. Wilpolt, their associates in the New Mexico work, for aid in the field, especially in the stratigraphic aspects of the problems. President C. E. Needham of the New Mexico School of Mines introduced the authors to the Los Pinos region and was first to call attention to the silicified breccias on the cuestas southwest of the range. D. F. Kent did the drafting.

CLIMATIC CHARACTER OF THE INTERVAL BETWEEN THE JURASSIC AND CRETACEOUS IN NEW MEXICO AND ARIZONA

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Albuquerque, New Mexico

ABSTRACT

In many places in New Mexico and Arizona a kaolinized, white horizon has been noted at the top of the Morrison formation (Jurassic) immediately under the Dakota (Cretaceous). In general, this is kaolin-cemented, white sandstone, but in Rio Arriba County, New Mexico, there occurs a nearly pure, white, massive kaolinite in small lenses at the contact between the formations.

The kaolinization is of such widespread distribution that it may be useful as a horizon-marker in drilling operations, and it indicates that a moist climate prevailed during a part, at least, of the time between Jurassic and Cretaceous deposition in this area.

INTRODUCTION

The upper Jurassic in New Mexico and Arizona is represented by the Morrison formation,[1] and the upper Cretaceous by the Dakota formation. The interval between represents a relatively long period of subaerial weathering and a change from fresh-water to marine deposition. The occurrence of kaolin in small lenses at various localities where the contact between the formations is exposed, and the widespread distribution of a kaolin-cemented sandstone at the contact, afford some new evidence on the climate of the interval.

THE OCCURRENCE OF KAOLIN

On Mesa Alta in the southeast portion of Rio Arriba County, New Mexico, west of the Rio Chama and just north of the Rio Puerco (del Oriente), the upper beds of the Morrison formation consist of buff-colored, medium-grained sandstone interbedded with a few thin lenses of conglomerate. The latter consists of well-rounded pebbles of quartzose or feldspathic material, $\frac{1}{8}$–2 inches in diameter, the feldspars concentrically weathered to a chalky consistency. Both the gravelly phase and the buff sandstone are cross-bedded at least in places and for the most part constitute a slope-forming member of the formation.

The overlying Dakota in this locality is a brown to buff-colored, medium-grained sandstone conspicuously cross-bedded and includes gravelly phases similar to those in the Morrison. The Dakota is well cemented and definitely a cliff-forming member.

In the Mesa Alta locality the contact between the Morrison and Dakota formations is distinctively marked by the presence of kaolin. The kaolin occurs in some outcrops as a lens of massive kaolinite, in other outcrops as a part of the cement in a white sandstone. In still other places the kaolin is present as a sandy white clay interbedded with thin layers of white sandstone or, less commonly, with lenses of limestone. The character of the zone containing kaolin varies sharply within short horizontal distances.

Massive kaolinite occurs on the west hillside overlooking the Cañada del Ca-

[1] Nomenclature clarified by A. A. Baker, C. H. Dane, and J. B. Reeside, Jr., "Correlation of the Jurassic Formations of Parts of Utah, Arizona, New Mexico, and Colorado," *U.S.G.S. Prof. Paper 183* (1936).

mino, one of the grassy valleys draining the top of Mesa Alta. The deposit is approximately 1 mile north of the south escarpment of Mesa Alta and about 12 miles by road northwest of the village of Youngsville. Here the basal 15 feet of the Dakota sandstone contains no trace of the kaolinitic cementing material. The contact with the underlying Morrison dips slightly to the east at about 1.5 feet per 100, but the two formations are parallel. Immediately under the Dakota is a ½-inch layer of white, soft, clayey sand which grades downward into a sandstone cemented by kaolinitic material. This sandstone, in turn, grades into gray sandstone which in places contains small inclusions of smooth, gray kaolinite. This grades into a smooth homogeneous, gray kaolin, pure except for some grains of quartz, and this, in turn, into a pure, white, massive kaolinite which, though easily scratched with a knife, gives the appearance of being more slaty than chalky. From the base of the Dakota to the base of the white kaolinite is about 7 feet.

Underlying the kaolinite and separated by a well-defined joint plane is a white sandstone cemented by kaolin. Within a vertical distance of 15 feet this grades into a buff, cross-bedded sandstone typical of the upper Morrison of this locality.

The section just described has been exposed by hand quarry operations, but owing to the soil mantle it is difficult to determine the exact shape of the deposit. It appears to be in the form of a lens extending approximately 300 feet in a north-south direction along the outcrop. The lens extends an unknown distance west into the ridge, but on the west slope of the ridge, a straight-line distance of about ½ mile, the white kaolin does not occur. Instead, there is a gray kaolinite, which is pure except for the inclusion of some quartz grains, and which turns nearly white when dried. Outcrops of the contact on ridges lying east of the main deposit of the Cañada del Camino show an impure white kaolin interbedded in places with sandstone, the grains of which are cemented with kaolinitic material.

The writer has inspected samples of a pure white kaolin from two other de-

FIG. 1.—Massive kaolin in quarry, Cañada del Camino, Mesa Alta.

posits—one on Mesa Alta about 5 miles east of the Cañada del Camino, the other roughly 4 miles south of the village of Coyote and 9 miles southeast of the main deposit already described. The kaolin of these samples is practically identical with that in the quarry.

In the main quarry the white kaolin has an irregular joint pattern, the best developed set striking N. 21° E., dipping 81° W. and 4–8 inches apart. A less well-defined vertical set of joints strikes N. 69° W. Horizontal jointing probably related to weathering is also apparent.

Figure 1 is a photograph of the kaolin in the main deposit where quarrying has exposed the section. The joint planes are

coated with a blackish varnish, probably a manganese salt deposited from ground water. Figure 2 shows the kaolinitic sandstone 1 mile southeast of the main quarry.

FIG. 2.—Dakota overlying Morrison white, chalky sandstone cemented with kaolin, near south escarpment of Mesa Alta.

A microscopic examination of the white kaolin showed it to be nearly pure kaolinite. A chemical analysis of the same material gave the results[2] shown in Table 1. Microscopic examination of the

TABLE 1

	Per Cent
Silica	46.82
Alumina	38.11
Magnesia	.09
Lime	.17
H_2O at 105° C.	.36
H_2O above 105° C.	13.46
Total	99.01

gray kaolin of the outcrop ½ mile east of the Cañada del Camino quarry showed that it is composed mostly of kaolinite with quartz grains which were included when the kaolin was deposited.

[2] Microscopic examination by Cornelius S. Hurlbut, Jr., Harvard University. Identification on the basis of index of refraction.

Chemical analysis by Earl Emendorfer, New York City, at request of Dr. Paul F. Kerr.

OTHER OCCURRENCES OF THE KAOLINIZED ZONE

The contact between the Morrison and Dakota formations was examined in many localities in northwestern New Mexico. Except for the three outcrops on and near Mesa Alta, no occurrence of pure white kaolin was found; but at nearly all the sections inspected the contact between the two formations is characterized by a whitened layer, in most places sandstone, the cementing material of which is white and of a kaolinitic composition. The whitened zone is very distinctive at Mesa Alta, in outcrops near the Arroyo Salado in the Nuestra Señora de la Luz de Lagunitas Grant,[3] near the confluence of the Rio Puerco and Rio San Jose near Suwanee, at Inscription Rock (El Morro National Monument), and south of Las Vegas, New Mexico. Field work did not extend to outcrops of the Comanche series in eastern New Mexico.

The stratigraphy of sections through the contact varies from one place to another. Table 2 gives descriptions of sections from different localities.

Channeling of the upper Morrison beds has been noted in a number of localities, but the maximum relief in outcrops east of Gallup, New Mexico, apparently does not exceed a few feet. Figure 3, photographed in the Lagunitas Grant near the Arroyo Salado, shows channeling in the white to greenish, shaly clay of the uppermost Morrison. The overlying Dakota is a medium- to coarse-grained sandstone, mostly of subangular

[3] Location near Francis' Ranch, as shown near center of Plate 19, C. B. Hunt, "Geology and Fuel Resources of the Southern Part of San Juan Basin, New Mexico," *U.S.G.S. Bull. 860-B*, Part II (1936).

TABLE 2

	Feet
Cañada del Camino, Mesa Alta, north of Youngsville, N.M.:	
Cross-bedded brown to buff, medium-grained sandstone, conglomeratic in places (Dakota)	15
White, soft sandstone, grains cemented with kaolin grading into pure white massive kaolinite (Morrison)	7
White sandstone cemented with kaolin grading abruptly into buff, medium-grained sandstone with local lenses of quartzitic and feldspathic conglomerate	10
West face, Mesa de los Viejos, north of Abiquiu, N.M.:	
Thin-bedded, buff, quartzose, sandstone, cross-bedded	15
Gray quartzose sandstone with large fragments of carbonaceous material, mostly lignite (Dakota?)	7
White quartz sandstone, cemented with white clay material, weathering to caves (Morrison?)	10
Massive white sandstone, no white clay between grains, cross-bedded in lower part	10
Near Arroyo Salado, Lagunitas Grant south of Cabezon, N.M.:	
Carbonaceous shale	1
Thin-bedded sandstone with layers of carbonaceous shale, mostly lignite (Dakota?)	8
Massive white sandstone, bands of limonite staining, grains quartzose, subrounded to subangular, subrounded with white powdery clay (Morrison?)	25
Light green claystone	1½
White sandstone, some white clay between grains	3
Near Window Rock, Arizona:	
Shaly sandstone with thin carbonaceous layers	6
Shaly lignite (Dakota?)	2
White medium-grained sandstone, cemented with white clay; conglomeratic and cross-bedded at base (Morrison?)	15
Hematite stained medium-coarse grained sandstone containing conglomeratic phases	100

grains of quartz, cemented by a white material, and including a few concretionary fragments of the underlying

FIG. 3.—Contact of Morrison greenish-white, shaly clay beneath the overlying Dakota sandstone. Note channeling. Lagunitas Grant near Arroyo Salado.

FIG. 4.—White kaolin in small channels just below contact of Morrison and Dakota, near Suwanee, New Mexico.

Morrison. Figure 4, photographed near Suwanee at the confluence of the Rio San Jose and Rio Puerco, shows channels of nearly pure kaolin occurring in a greenish clay full of gypsum crystals, the

latter probably recent crystallization from ground water. The overlying Dakota is a buff conglomeratic sandstone. The greenish clay rapidly fell apart when immersed in water.

Parry Reiche describes the section 6 miles north of the northern escarpment brown, coarse, ill-sorted subangular to subrounded sandstone, fairly well-cemented, with low-angle cross-bedding and much channeling."[4]

From this description it appears that the old surface increased in relief to the west, but decomposition of feldspathic

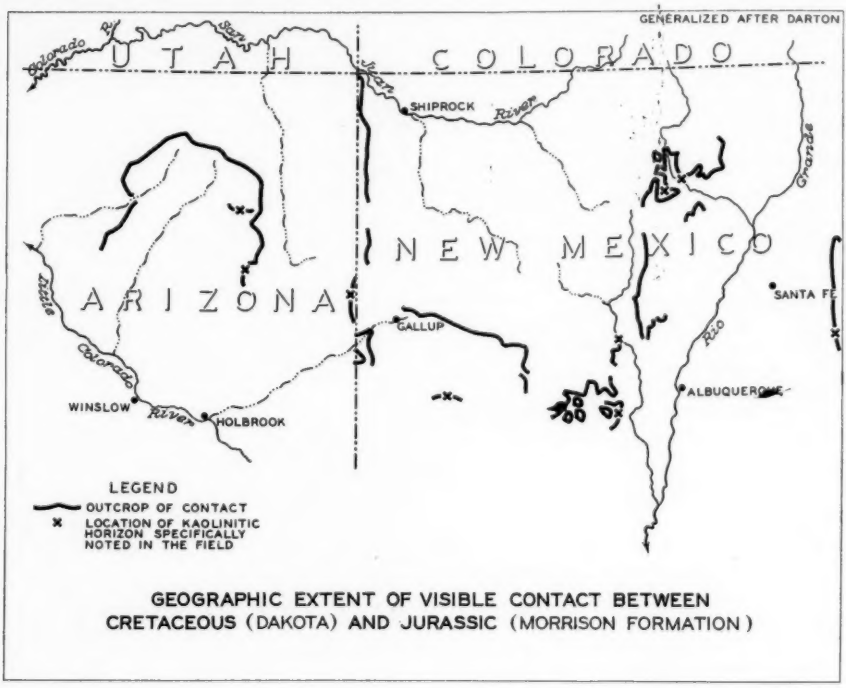

FIG. 5.—Generalized map showing linear extent of outcrops where contact of Jurassic and Cretaceous is exposed. Observations at Steamboat and Waterless Mesa, Ariz., and Chapelle, N.M., by Parry Reiche, unpublished notes.

of Waterless Mesa and 20 miles west of Chinle, Arizona: "At the top of the Morrison . . . . is a dead white, very coarse, cemented, ill-sorted sandstone precisely like that on the top of Inscription Rock" (El Morro National Monument) south of Grants, New Mexico. The white sandstone above "is characterized by angular, coarse grains which resemble chalk, probably kaolinized feldspar. . . . . Below this sandstone is a buff to light material into clays, leached to a light color, also prevailed in this area.

The white zone of kaolin-cemented sandstone, though widespread in its occurrence, may be, in certain places, not a distinctive feature and may be too thin to show itself in well cores with certainty. However, the general features of the contact between the two formations as described in this study give some new cri-

[4] Unpublished notes.

teria which may be useful in search of a horizon-marker in drilling operations. Table 3 gives descriptions of cuttings from a well drilled by the Ambrosia Company north of Grants, New Mexico. Only that section of the log near the contact of Dakota and Morrison is described.

TABLE 3

WELL LOG, AMBROSIA COMMITTEE NO. 1, SE¼, SEC. 11, T 14 N, R 10 W, MCKINLEY COUNTY, N.M.; DRILLED WITH CABLE TOOLS

	Feet
Fine, clean, white quartz sand; occasional lignite fragments with numerous coal fragments	135– 45
Gray, ill-sorted, silty sandstone	145– 55
Gray, sorted, very fine sand and abundant argillaceous lignite	155– 85
Light greenish gray, soft claystone	185–205
Same, with abundant quartz grains	205– 15
Same, about half the claystone fragments dull maroon	215– 25

In this well the Dakota formation persists to a depth of 185 feet, and the upper Morrison probably begins at this depth. The greenish claystone is similar to that in outcrops near the Arroyo Salado. No layer of kaolin-cemented sand is apparent at the contact in this well.

The log indicates that the kaolin is not everywhere present at the contact, as certain outcrops show, and in places a white clay-cemented sandstone may occur in the Morrison, well below the contact. This does not necessarily rule out the possibility of using the kaolin as a marker-bed in other localities. Erosion on the old surface may have removed any traces of kaolinization. The sandstone member of the upper Morrison does not occur in some localities and is represented by shaly beds. The kaolinization is apparent only where the sandstones exist and probably is not a characteristic feature where the upper Morrison is predominantly shale.

ORIGIN OF THE KAOLIN

The origin of the white clays of Georgia was discussed by O. Veatch,[5] and essentially the same theory accepted by Fred R. Neumann[6] for the similar clays in South Carolina. Veatch postulates weathering of the Piedmont land surface from Cambrian to Cretaceous time. The deep residual soil thus formed from the igneous rocks was washed away following uplift at the beginning of the Cretaceous and deposited as alluvial fans or as deltas at the mouths of streams. The white clays were accumulated in offshore lakes, sounds, or landlocked arms of the sea, freshened by runoff from the land. Veatch believes the clays were deposited in fresh water because lime or calcareous layers do not occur in the clay beds. Neumann accepts this theory except that he believes the clays to have been laid down in salt water, pointing to the absence of banding in the clays which might be expected in lacustrine deposits. He postulates that the original residual soil was leached of its iron, leaving the white clays which later were carried to the sea, coagulated by the salts in the sea water, and deposited in quiet areas between deltas. The massive character of the lenticular clay beds he ascribes to rapid deposition.

The Morrison formation, according to Baker, Dane, Reeside,[7] and other workers, was deposited by rivers and in lakes on a little-dissected and poorly drained surface, perhaps under semiarid conditions. These authors state that the upper boundary is certainly a plane of marked

[5] "Kaolins of the Dry Branch Region, Georgia," *Econ. Geol.*, Vol. III (1908), pp. 109–17, and "Second Report on the Clay Deposits of Georgia," *Ga. Geol. Surv., Bull. 18* (1909), pp. 97–103.

[6] "Origin of the White Clays of South Carolina," *Econ. Geol.*, Vol. XXII (1927), pp. 374–87.

[7] *Op. cit.*, p. 55.

erosional unconformity though there are differences of opinion as to the location of this boundary where the Morrison, as they interpret it, contains conglomeratic beds in the upper part.

The kaolinitic cementing material in the white horizon near the contact probably was derived by weathering of feldspathic minerals on this surface during the long time between the deposition of the Morrison and Dakota sediments. W. G. Woolnough[8] points out that the nature of the residual surface products of chemical weathering during the final stages of peneplanation offers a criterion for determining the climatic characteristics prevailing during that period. If the bulk of the residue *in situ* be silica, gibbsite, and kaolinite, he believes the climate was rather uniformly moist, in contrast to the alternation of saturation and desiccation which has given the concretionary, amorphous crust developed in parts of Australia.

This reasoning suggests the development of kaolin on the surface of the Morrison sediments from decomposition of the feldspathic materials during a moist period. The few lenses of pure kaolinite might easily have been formed by local concentration of the fine white clay in small shallow lakes on the old surface. These lakes could also account for the thin lenses of limestone which occur near the kaolin and at about the same horizon on the Mesa Alta outcrops. Subsequent deposition of the Dakota began with a re-working of the surface material on the old plain, mixing the kaolin with sands, removing all traces of kaolin in places, and covering a few small lenses of kaolinite without disturbance other than shallow re-working of the uppermost layers.

ACKNOWLEDGMENTS.—The author gratefully acknowledges the constructive criticism and assistance of Dr. Parry Reiche, who also furnished many valuable field observations. The author is indebted to Mrs. Alice C. Myers, of Santa Fe, who first informed the author of the existence of the kaolin, for specimens, location descriptions, and chemical analysis of the kaolinite, and to Cornelius S. Hurlbut, of Harvard University, for making microscopic identifications of minerals.

[8] "Origin of White Clays and Bauxite and Chemical Criteria of Peneplanation," *Econ. Geol.*, Vol. XXIII (1928), pp. 887–94.

REVIEWS

Source Beds of Petroleum. By PARKER D. TRASK and H. WHITMAN PATNODE. Report of investigation supported jointly by the American Petroleum Institute and the Geological Survey of the United States, Department of the Interior, from 1931 to 1941. Results of A.P.I. Research Committee No. 4. Work done under Advisory Committee composed of R. F. BAKER, B. B. COX, F. R. CLARK, K. C. HEALD, W. B. HEROY, L. P. GARRETT, F. H. LAHEE, A. W. MCCOY, H. D. MISER, R. D. REED, L. C. SNIDER, and others. Tulsa, Okla.: American Association of Petroleum Geologists, 1942. Pp. 566; figs. 72. $4.50.

Geologists have been employed by oil companies for twenty-five or thirty years in the search for new oil fields. Most of their time has been spent looking for structures or rock traps which might hold oil. At first this was logical, for, with the assistance of the "wild-catter" who ventured out into the unknown, they generally knew when they were in oil territory. The widening search for oil in areas far from known fields has, in recent years, developed such an interest in the origin of oil that the American Petroleum Institute, on the advice of members of the American Association of Petroleum Geologists, started in 1926 a research project on source beds of petroleum. The fact that the industry itself should undertake basic research of this kind marks a new era. Many leading petroleum geologists co-operated in this investigation by serving on committees, assisting in the collection of samples, and by criticism and advice as the work progressed. The project was initiated and carried on for nine years under the chairmanship of K. C. Heald. The committee which brought it to completion was headed by Ben B. Cox, while Hugh D. Miser supervised the activities of the United States Geological Survey in this enterprise.

Source Beds of Petroleum should be regarded as the last of a series of progress reports made during the fifteen years this project has been under consideration. The first five years' work was published by the senior author in 1932.[1]

The book here reviewed presents the results of ten years' research on sedimentary rock samples obtained from eight principal oil-field areas of the United States. Approximately 35,000 samples were examined, most of them from wells drilled for oil. Although the title might imply that source beds are definitely known, it is made clear in the introductory statement that the purpose of the investigation was to "determine the diagnostic criteria for recognizing source beds."

The authors first discuss their methods of determining the twelve properties which were studied: (1) texture; (2) organic content; (3) carbon content; (4) reduction number, a measure of the amount of chromic acid that can be reduced by the sediments under given conditions; (5) nitrogen content; (6) color; (7) assay number, a measure of the volatile organic substances in the sediments; (8) relative volatility, the ratio of the assay number to the reduction number and a rough measure of the degree of volatility of the organic constituents; (9) nitrogen-reduction ratio, which is a hundred times the ratio of the nitrogen content to the reduction number and is a very crude measure of the degree of oxidation of the sediments; (10) the oxidation factor, the ratio of the carbon content to the reduction number and a rough measure of the state of oxidation of the sediments; (11) carbon-nitrogen ratio; and (12) calcium carbonate content. These properties were studied because they could be determined quite rapidly for a large number of samples.

The heart of the book, and the part of greatest interest to petroleum geologists, covers three hundred pages under the heading "Regional Studies." Here are presented in detail the results of tests made upon samples from the eight oil-producing areas of the United States: Los Angeles Basin, Central California, Rocky Mountains, Mid-Continent, West Texas, East Texas, Gulf Coast, and the Appalachian area. The results are shown in tables and diagrams. The locations of wells from which samples were

[1] P. D. Trask, *Origin and Environment of Source Beds of Petroleum* (Houston: Gulf Publishing Co., 1932), 323 pp. This report of the first five years' work on the study of source beds contains a list of references of all previous reports published about the work.

obtained are shown on sketch maps. Petroleum geologists will, naturally, turn to the chapters under "Regional Studies," which have to do with the areas in which they are interested and from which they have contributed samples and stratigraphic information. Since most of the sediments that were investigated came from California, 14,000 of the 35,000 analyzed being from that state, it is logical that the results from that area are given first place in the book. Areas outside California are not so thoroughly represented; for instance, only 500 samples from three wells in as many producing fields came from the West Texas area, and samples from these contained so little organic matter that further studies were not undertaken; hence, the properties of sediments from the West Texas area are of doubtful value.

The investigations have shown that a number of properties of sediments which have previously been looked upon as indicators of source beds do not have a definite relation to oil zones and, presumably, are not favorable indicators of source beds. The authors feel that organic content, color, texture, carbon content, and nitrogen content should not be looked upon as having any definite relation to oil-bearing beds, as tests of these properties on many thousands of samples gave conflicting and contradictory results. From this it should not be inferred, however, that these properties are not found in source beds. Although oil is found where the organic content is high and also where it is low, oil may be absent under these same conditions. The fact that definite relations to oil-bearing beds have not been established should not alter the opinion of many geologists that some marine shales and limestones are source beds. The authors' conclusions may lead to the determination of some other diagnostic property, and they suggest that the degree of oxidation as expressed by the nitrogen-reduction ratio may prove valuable.

The authors say that the nitrogen-reduction ratio has a fairly definite relationship to the occurrence of oil, being low in sediments closely associated with known oil zones and generally high in barren beds or in sediments remote from known oil zones. They believe that its value lies in prospecting new territory. For nitrogen-reduction studies well samples are necessary, as they found that weathering effects prohibit the use of surface samples. This means that the nitrogen-reduction ratio cannot be applied in new territory until a well or core hole has been drilled which will yield proper samples; furthermore, their work, so far, in developing the nitrogen-reduction ratio has been mostly on samples within 500 feet vertically of known producing beds. Just how far favorable indications could be extended horizontally has not been clearly developed, but areal changes are not considered rapid in the same stratigraphic horizon. It was found that the nitrogen-reduction ratio became progressively higher within 500 feet upward from the oil zone, while in the 500 feet below it no definite relations were found. From this the authors concluded that oil migration has been upward. Favorable nitrogen ratios lie between 3.0 and 10.0, although some areas in which the ratios are more than 8.0 are looked upon as unfavorable. This ratio cannot be used for the location of oil fields, as it exhibits no relation to structure, being the same whether on or off favorable oil structure; however, the authors believe it is a tool for regional interpretation. The relationship of the nitrogen-reduction ratio to oil zones prevails in seven out of the eight oil provinces studied. While attention is called to the nitrogen-reduction ratio as a possible working hypothesis, further work should be done to prove its value, and it is hoped that petroleum geologists venturing into new territory may carry on further experimental work which may help develop this method of approach.

Source Beds of Petroleum is not a book for casual reading; it must be studied and digested in order for one to understand the great mass of experimental data which have been developed. The authors, by their study of samples of sedimentary rocks from many areas, have contributed greatly to the knowledge of conditions in many oil-bearing areas. It is regrettable that they were not given time to explore further into the nitrogen-reduction ratio and other properties which express the degree of oxidation of sediments. Also, in addition to the seeking of facts, they should have been encouraged to express fully their opinions and deductions. While the volume published is essentially a book for specialists in petroleum, the scientific methods of analysis and the statistical presentation of experimental data are bound to serve as guides for other investigators who undertake the study of sedimentary rocks, and the lists of references to material previously published will be of great assistance to students of these subjects. The investigation of properties of sedimentary rocks from our oil fields has just started, and it is

gratifying to know that, through the efforts of K. C. Heald, the Gulf Oil Corporation at Pittsburgh, Pennsylvania, has prepared facilities for storing the 35,000 samples in a fireproof building where they will be labeled and arranged in uniform files so that they may be readily consulted. It is quite certain they will be used for further investigations of radioactivity, colloidal content, metallic and organic catalyzers, effects of bacteria, and other characteristics which remain to be investigated in connection with the problem of the origin of oil. The American Petroleum Institute, the United States Geological Survey, and the geologists who have worked with them on various committees should be congratulated for having chosen scientists like Trask and Patnode to carry through a work of this kind.

THERON WASSON

Geologic Reconnaissances in the Chinese T'ien-Shan: Reports from the Scientific Expedition to the North-western Provinces of China under the Leadership of Dr. Sven Hedin, "The Sino-Swedish Expedition," Publication 16, III, 6: *Geology*. By ERIK NORIN. Appendixes by F. HERITSCH, F. KAHLER, and B. BOHLIN. Stockholm: Tryckeri Aktiebolaget Thule, 1941. Pp. 229; figs. 33; pls. 23; 3 maps and 1 plate of sections in pocket.

The results of these reconnaissances by the Sino-Swedish expedition of 1928–31 have been grouped in five chapters on the orography of the Chinese Tien Shan, the Lower, Middle, and Upper Paleozoic formations, and the igneous rocks. In each chapter the rocks of each of the three great facies zones of the Tien Shan (the northern, central, and the southern zone including the Tarim Basin border region) have been treated separately. Chapter vi, "The Geologic History of Tien Shan," summarizes our present knowledge and compares the formations of the eastern Tien Shan with those of the western Tien Shan which have been studied in recent years by the Russian surveys.

An important outcome of this expedition is recognition of the wide distribution of Lower Paleozoic formations in the Tien Shan and Nan Shan ranges. Upper Cambrian and Ordovician beds are most extensively exposed within the southern zone and extend at least over a considerable part of the southern foreland, Serindia, where the strata are only slightly disturbed in striking contrast to the strongly deformed younger formations within the Tien Shan geosynclinal zone farther north. In the central zone a large part of the geosynclinal sequence from the Lower Paleozoic to the Permian is represented, together with granitic intrusions which surface large areas. Along the northern border of the geosynclinal zone in the Russian Tien Shan (as in the eastern Urals which are closely related) evidence of the Taconic orogeny is found, and likewise in the Nan Shan deformation took place in the transition from Ordovician to the Silurian.

The rocks of the Chirgöstaü series (presumably Devonian) record a period of intense volcanic activity with few parallels in the geologic record of Central Asia, excepting perhaps the volcanism in the second half of the Permian. The volcanics are particularly extensive in the northern Tien Shan. The Variscan granitic intrusives are concentrated in the central zone of the Chinese Tien Shan and are of at least two generations—a pre-Visean (Lower Carboniferous), which is apparently an accompaniment of Bretonian folding, and more widespread late Variscan intrusions, which may be correlated with the Asturian orogenic phase. Between the two occurred the Visean transgression which was the most widespread of the late Paleozoic submergences in Central Asia.

The Permian sandstones of Rotliegende facies in the western Tarim Basin are of special interest because they appear in the wide gap between the large areas of similar deposits in Europe and North China, both of which show a transition from marshy coal-producing conditions to red sandstones and conglomerates. In the Tarim Basin marine equivalents play a more important role because this area was probably on the very edge of the Serindian land.

The author's researches on the Mesozoic formations of the Tien Shan are not included in this volume because, by agreement, the paleontological material was delivered to the Geological Survey of China to be studied by the Chinese geologists. Within the Mesozoic and Tertiary came the "germanotype deformation (normal faulting) of Tien Shan by which it gradually obtained its present features." Broad surfaces of denudation, recording periods of relative quiescence, give a plateau-like appearance to large parts of the mountain complex. Dislocation and uplift at the end of the Tertiary were responsible for the present elevations of the ranges, while massive conglomerates accumulated in the neighboring basins.

The rugged heart of Asia must hold the key to many geologic problems, and this report, giving the broad outlines of the geology of an important part of it, is a notable contribution. The reader, however, would have obtained a better understanding with less effort if a generalized map of the great ranges and basins of Central Asia had been presented in the opening chapter.

R. T. C.

Reports of the Great Barrier Reef Committee, Vol. V. By H. C. RICHARDS and DOROTHY HILL. Brisbane: A. H. Tucker, Government Printer, 1942. Pp. 122; figs. 2; pls. 12.

In 1923 the Great Barrier Reef Committee was formed for the purpose of investigating the nature and origin of the remarkable coral-reef formation which parallels the eastern coast of Australia for 1,200 miles. The present report gives the results and conclusions obtained from boring operations at two points about 700 miles apart. The Michaelmas Cay bore (Lat. 16°36′ S.), about halfway along the length of the reef and as close to its outer edge as possible, was put down to a depth of 600 feet, while the Heron Island bore (Lat. 23°26′ S.), near the southern end of the reef and 44 miles from mainland, reached a depth of 732 feet. In the former the coral-reef rock was 378 feet thick and in the latter 506 feet (84 fathoms); below this in each case were quartz foraminiferal sands. In neither bore was the basement rock reached. Because the maximum depth for coral-reef growth is about 25 fathoms, the authors conclude that subsidence to the extent of 60 fathoms must have occurred near Heron Island during the formation of the reef.

As Iredale's study of the Mollusca indicates that the 226 feet of sands and hard bands below the reef rock were also shallow-water deposits, probably formed in water less than 6 and certainly not more than 30 fathoms deep, the authors believe that subsidence of at least 100 fathoms is indicated. Furthermore, since all the corals and Mollusca are those inhabiting the same seas today, the climate has not varied greatly during the subsidence; the deposits show no sign of the Pleistocene ice age and are thought to be clearly later than this.

Each of the 77 samples from the 732-foot Heron bore is described in detail with a complete chemical analysis; from the Michaelmas bore the samples are spaced somewhat more than 10 feet apart. Great similarity between the deposits at the two localities is indicated. Both show an absence of dolomitization, the presence of two aragonite zones, and insufficient cohesion to yield cores comparable to those obtained at Funafuti and the Bahamas.

In two appendixes are reports on the Foraminifera by Joseph A. Cushman and on the Mollusca by Tom Iredale.

R. T. C.

Stratigraphic Type Oil Traps. Edited by A. I. LEVORSEN. Tulsa: American Association of Petroleum Geologists, 1941. Pp. xii+902; figs. 300, 5 folding sheets in pocket. $5.50 (members, $4.50).

Stratigraphic-type oil traps were defined by Levorsen in 1936 as those "in which a variation in the stratigraphy is the chief confining element in the reservoir which traps the oil." During the past decade petroleum geologists have become increasingly aware of the importance of stratigraphic traps in their search for oil. Whereas methods of discovering structures have been raised to relatively high levels of development, there is essentially no recognized technique for finding stratigraphic traps. Perhaps the first step in developing a method of approach is to study known examples of stratigraphic oil occurrence. For this purpose the present volume is eminently satisfactory.

Stratigraphic traps are bounded on one or more sides by nonporosity, due to any cause except structural deformation. Many stratigraphic traps are lenticular or elongated sand bodies; others are caused by variations in porosity and permeability of limestone; some are updip feathered edges of sand along old strand lines. To a large extent the location of stratigraphic traps depends upon the development of methods for finding porosity edges. This is mainly a problem in sedimentation, and the authors of the thirty-seven papers in this symposium stress the sedimentary history of the traps they describe.

A representative number of stratigraphic-type traps were chosen from various regions of the United States to serve as examples of this kind of accumulation. Although each paper has its own style and organization, all of them include detailed discussions of the general geology, the stratigraphy, and structural features of the pool, as well as details of the producing sands. In all instances the factual material is

stressed, to give as clear a picture as possible of the situation. The geologic history of the area is reviewed, and sedimentary and other factors which caused localization of the oil are described. All the papers are well illustrated with maps and diagrams.

The volume takes its place alongside the earlier A.A.P.G. symposium on *Structure of Typical American Oil Fields* (1929), and, like its predecessor on structural traps, it will do much to organize contemporary thought about stratigraphic traps. Not only is the volume indispensable to the practicing petroleum geologist, but the teacher and student of petroleum geology will gain many new ideas from it. The emphasis on sedimentation makes the book valuable as a reference in courses on that subject also, especially those phases which are of importance in practical applications of the science. Certainly an analysis of the papers included in the symposium brings home the importance not only of detailed studies of sediments themselves but also of principles of sedimentation and stratigraphy in providing a sound basis of interpretation for future exploration.

W. C. KRUMBEIN

Silurian System of West Virginia. By HERBERT P. WOODWARD. Morgantown: West Virginia Geological Survey, Vol. XIV, 1941. Pp. viii+326; figs. 12; pls. 33.

This report, which is the initial volume of a projected series treating the systematic geology of the state, contains the first description under a single cover of the Silurian rocks of West Virginia. Volumes of this sort are particularly useful to geologists in other states and in distant regions because the descriptions and problems are treated from a somewhat comprehensive point of view with local details kept subordinate. Interesting to many geologists will be the discussions of the lower and upper limits of the Silurian system in West Virginia, both of which are still matters of controversy. The author takes as the lower limit the base of the Tuscarora sandstone, although the West Virginia Survey has long held the view that the underlying Juniata and Oswego formations are also of Silurian age. One may note parenthetically this wholesome attitude of the survey which sanctions in its publications opinions at variance with its adopted usage. As the Juniata formation is confidently correlated with the widespread Richmond of the interior, much more than the Appalachian region is involved in the problem.

The uppermost definitely Silurian formation of West Virginia and the adjacent Appalachian region is stated to be the Tonoloway limestone of Cayugan age. The overlying Keyser limestone remains a bone of contention. Recently there has been a tendency to place it in the Silurian with the waterlimes of New York, but in this volume it is included in the Helderberg group of the Devonian.

The stratigraphic (the major) portion of the report is effectively illustrated. The Silurian faunas are described and discussed, but without illustrations. A section on economic resources, an extensive bibliography, and a very detailed index complete the volume.

R. T. C.

Optical Mineralogy. By AUSTIN F. ROGERS and PAUL F. KERR. New York: McGraw-Hill Book Co., 1942. Pp. xvi+390; figs. 369; one colored plate (birefringence chart). $3.75.

This is the second edition of *Thin-Section Mineralogy* published in 1933 with 311 pages and 261 figures. Despite the change in title, there is no change in format or paper and

> the general form of treatment . . . . has been retained, but many explanations of optical properties have been rewritten, and a considerable number of new diagrams have been added. Descriptions of a number of additional minerals have been added, and the descriptions of a number of groups have been rewritten. . . . . Certain portions of the text have been reorganized . . . . although it still applies primarily to mineral identification in thin sections.

The main excuse for the new title is the introduction of a chapter on "Observation of Mineral Fragments" (11 pages), slightly expanded from material in chapters iv and vii of the old edition. Two new names are introduced: Rogers' "lamprobolite" for basaltic hornblende and Lodochnikov's "serpophite" for the amorphous constituent of serpentine.

A few minor errors were noted. Thus on page xvi it is stated that r = the dispersion for red; in Figure 29 blue and violet are interchanged; in Figure 51 the principal axis is not vertical; there is no double refraction in calcite with normal incidence perpendicular the optic axis (p. 65); in Figure 52 the rhomb angles are wrong; thickness should be millimicrons (top p. 69); the index ellipsoid is very different from the indica-

trix (p. 101); and the boundary between the first and second orders on the birefringence chart is misplaced; moreover, it lacks a boundary at the top of the fourth order. The analyzer technique given at the bottom of page 59 was described in *Science* in 1929 by C. Milton.

The first part (theory and determination) of the book has been increased by 22 pages. The addition of charts showing optical properties graphically will be valuable. The second part (description) has been increased by 51 pages. It contains many excellent photomicrographs. It is regrettable that, in general, graphs showing variation of composition with (optic) properties are omitted, but the authors wished to avoid undue expansion. This text is excellently suited for those who teach a brief course in optical principles from thin sections and who wish both theory and description in a single fairly small volume.

D. J. F.

Oil in the Earth. By WALLACE PRATT. Lawrence: University of Kansas Press, 1941. Pp. 106. $1.00.

The contents of this little book represent a series of four lectures delivered to the students of the Department of Geology of the University of Kansas in 1941. As such, it presumes some geologic background on the part of the reader.

The book is divided into four chapters consisting, respectively, of a portrayal of the general character of oil and oil fields; the occurrence and distribution of oil in the earth; an analysis of methods and achievements in the finding of oil; and some reflections on the utilization of oil by society. The author draws rather heavily upon statistical material but treats it in such a manner as to render it readable.

The success of Americans in the discovery of petroleum is attributed to the intelligent cooperation of all members of the industry from "roughneck" up. Additional factors in their success is the general knowledge of geology which permeates the entire industry and the frequency with which "wildcats" are drilled. Relative to this last point, it is stated that, while we have drilled one exploratory test for each 12 square miles of sedimentary rocks in this country, the rest of the world has drilled only one exploratory test for each 1,100 square miles of sedimentary rocks. The undersupply of oil on the part of the Axis nations is believed to be a function of lack of exploitation rather than owing to any primary scarcity of oil itself.

This book is recommended to those who wish a general picture of the petroleum industry in its broader aspects.

ERNEST P. DU BOIS

The West Highlands and the Hebrides: A Geologist's Guide for Amateurs. By ALFRED HARKER. Cambridge: University Press; New York: Macmillan Co., 1941. Pp. xxiii+128; figs. 81; maps 8. $2.00.

Alfred Harker's early work and notable contributions on the geology of Skye and other islands of the Inner Hebrides had made this region such a favorite of his that in his later years he paid many visits to the Western Highlands and neighboring islands for recreation and further study. The present volume is his attempt to interpret the scenery and rock structures, which he found so fascinating, for the benefit of visiting geologists and interested amateurs. Although at the time of his death in 1939 he had not quite finished the manuscript, it was so nearly complete that colleagues have been able to supply the missing bits and to publish the book essentially as Dr. Harker intended.

The general treatment is by ready routes of travel and short supplementary journeys along which the dominant aspects of the geology, and likewise the local features of particular note, are concisely described and their significance briefly indicated. Much of what is to be seen is also effectively portrayed by many of Harker's own sketches which are adequately lettered and explained. Together, they give the reader a very good picture of this region which has so much of interest. Well done, by a master of the subject, the book should arouse in the traveler following some of these routes a bit of the author's own eager, inquiring spirit.

A short, appreciative sketch of Harker's career by Alfred C. Seward (prefixed by photograph of the author in pensive mood aboard ship off the west coast) appears in the Preface.

R. T. C.

Paleozoic and Related Rocks of Southeastern Minnesota. By CLINTON R. STAUFFER and GEORGE A. THIEL. (Minnesota Geological Survey Bull. 29.) Minneapolis: University of Minnesota Press, 1941. Pp. viii+261; figs. 62.

This volume represents an important contribution to the stratigraphy of the Upper Mississippi Valley. It is organized into four parts.

The first, although brief, more than adequately describes the lithology of the strata which are encountered at the surface and in subsurface records of southeastern Minnesota. The formations discussed belong to the following systems: Archeozoic, Proterozoic, Cambrian, Ordovician, Devonian, Cretaceous, and Quaternary. The historical aspects of the formations are well treated with abundant citations and references to earlier workers.

The second, third, and fourth parts are entitled, respectively, "Composition of Minnesota Limestones," "Sections and Well Records," and "Faunal List."

The authors of this work propose the term "Root Valley" for the sandstone which lies between the Oneota and Shakopee dolomites. This is done on the basis that Shakopee fossils are found in dolomites interbedded with sandstones which have been called "New Richmond." The reviewer believes that this new term is proposed on inadequate grounds and that the term "New Richmond" should continue to be used for the main sandstone member of the Prairie du Chien while recognizing that it is variable in development and may be interbedded with either the Oneota below or the Shakopee above.

ERNEST P. DU BOIS

"Report of the Committee on Sedimentation, 1940–1941." PARKER D. TRASK, chairman. Washington: National Research Council, 1942. Pp. 110; tables 3. $1.00. (Mimeographed.)

In addition to the general report of the chairman, this report of the Committee on Sedimentation of the Division of Geology and Geography of the National Research Council comprises the following articles: "Tables for the Determination of Detrital Minerals," by R. Dana Russell; "Statistical Summary of Some Alluvial Gravels," by W. C. Krumbein; "Statistical Data on the Size-Distribution of Sands and Gravels from the Mississippi River and Its Tributaries," by August Goldstein, Jr.; "Sedimentation Studies by the Soil Conservation Service, 1940–1941," by Carl B. Brown; "Recent Papers Dealing with Marine Sediments and Sedimentary Processes," by Henry C. Stetson; "Recent Research on Sedimentation by Petroleum Geologists in the Gulf Coast Region," by F. W. Rolshausen; "Quantitative and Analytical Sedimentation," by F. J. Pettijohn; "Preliminary Study of the Bottom Sediments of Utah Lake," by H. J. Bissell; "Soil Changes Significant in Diagenesis Studies," by W. P. Kelley; and "Diagenetic Changes in Calcareous Sediments," by George A. Thiel. Much valuable material is presented in these contributions.

R. T. C.

Amos Eaton. By ETHEL M. MCALLISTER. Philadelphia: University of Pennsylvania Press, 1941. Pp. xiii+587. $5.00.

The biography of Amos Eaton is one which delves far back into the early beginnings of science in North America. His fame cannot be said to be the property of any one branch of science, for he was interested in, and contributed to, botany, stratigraphy, mineralogy, zoölogy, and chemistry. By his own admission, however, his chief fame lies in the development of geology in the "pre-Maclurean" page of its history. While this work is valuable to those interested directly in the life of Eaton, it is perhaps equally so to others for the side lights it throws upon the scientists of his day such as Torrey, Emmons, Hall, and Silliman. As a geologist, Eaton made two outstanding contributions: the first attempt to develop in this country a stratigraphic terminology which was not founded upon Wernerian principles and the most complete report, at that time, upon the stratigraphy of New York State. His work, in large part, provided the foundation upon which James Hall and Ebenezer Emmons based their later studies of New York. These studies in turn were the real beginnings of geology in this country. It may be concluded that it is difficult to overestimate the influence which this early scientist and pedagogue had upon the development of geological science as we now know it.

ERNEST P. DU BOIS

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